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BIOLOGICAL EFFECTS OF HIGH VOLTAGE AC TRANSMISSION LINES

With reference to the COLSTRIP PROJECT: GARRISON-SPOKANE HVTL

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COLSTRIP PROJECT: GARRISON-SPOKANE HVTL

A report to the

Montana Department of Natural Resources
and Conservation

Submitted to:

Montana Department of Natural
Resources and Conservation
Energy Division
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February 1983

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ABOUT the AUTHOR

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EXECUTIVE SUMMARY

This document reviews the issues that concern possible effects on human health from exposure to the electric and magnetic fields of a high voltage transmission line (HVTL), with particular reference to the proposed Bonneville Power Administration 500 kV ac transmission line to be built in Montana as a part of the Colstrip Power Project.

The principal issue concerns effects that might be caused by chronic exposure of humans to the HVTL fields with the result of an adverse change in human health or well being.

Present scientific knowledge about the effects of 60 Hz electric fields does not permit unequivocal determination of the extent of possible hazard to human health, but to date no health hazards due to 60 Hz HVTL electric fields are established. **A principal finding of this report is that results of several experiments with laboratory animals show there are biological interactions with electric fields at field strengths and frequencies relevant to human exposure in the HVTL environment.** These results are principally in the areas of animal behavior, neurophysiology, neurochemistry, ultra-structure of brain cells, and repair of fractured bone. There are strong suggestions of effects on body rhythms in rats, such as the circadian rhythms that underlie many biochemical cycles. In humans these rhythms are recognized as important to well being.

A number of related experimental data that involve electric field exposure to laboratory animals is in support of these findings. Physiologic effects on nervous system tissues have been demonstrated in vitro using fields stronger than those the transmission line would create at ground level. Neurochemical studies of isolated brain tissue show field and frequency-dependent changes at frequencies close to 60 Hz. Pulsed magnetic fields (that produce electric fields of an uncertain magnitude, probably many times greater than relevant HVTL electric fields in tissue) alter bone growth and repair. The changes in bone are associated with biochemical changes. Perception of the field by several species, including humans, pigeons, and baboons is well established.

The mechanisms that underlie the observed effects are not clear. Evidence is lacking to show that effects are due to superficial stimulation of sensory systems of the skin, nor is this mechanism disproven. Neither is there a determination that effects at the relevant field strengths involve the direct action of internal body currents on cells.

Overall, major advances have been made recently in the research into biological effects and in accompanying research on appropriate dosimetry of persons and animals in the field, but resolution of the scientific issues in the immediate future is not likely.

Having established that certain effects occur, an examination of these effects, and the abundant literature on electric field related physiological responses in animals and the far less definitive data on man, shows that there are no confirmed pathological changes proven to be related to HVTL fields. This leads to the conclusion that **while effects occur, they are generally not of a pathological nature.**

Definitive data on biological effects and hazards are not at hand, yet it is a practical necessity to establish criteria for those electric field strengths to which the public can be exposed with a very high degree of confidence that health is not adversely affected.

The scientific data and a comparison of HVTL electric fields to the fields now accepted in the home or workplace environment lead to the conclusion that **HVTL fields are of a magnitude that requires specification of a limitation on the electric field strength to which members of the general public should be exposed on a chronic basis**, as would occur at a homesite or workplace. It is agreed that specification of a maximum electric field strength at the edge of the right of way is a suitable means to regulate HVTL fields. However such a standard is not ideal, and alternatives to a standard for the edge of the right of way field strength may be considered preferable.

It is recommended that limitation of the vertical component of the electric field at the edge of the right of way to a maximum value of 1 kV/m rms (1000 volts per meter) is a prudent requirement for operation of the Colstrip HVTL with little likelihood that persons chronically exposed to the HVTL electric and magnetic fields would suffer any adverse effects.

Acute effects of HVTL electric fields are better understood and do not require imposition of any restrictions on electric field strength either within or outside of the right of way (ROW). Problems with electric currents induced in large metallic structures (e.g., fences parallel to the HVTL, above ground irrigation pipes, metal-roofed buildings, etc.) are well known and pose no hazard if sound engineering and construction practices are followed. There is inadequate knowledge of the safe current levels at 60 Hz for small children, and their safety under worst case conditions within the right of way is not well determined.

Within the ROW, shocks ("spark discharges") may be readily perceived by most persons under various practically occuring conditons. Where needed, methods to reduce the occurrence of spark discharges are available. Some persons would find the shocks annoying, and an accident due to a startle response may occur, but these effects and the direct action of the field itself do not pose a health hazard.

SUMMARY OF 60 Hz BIOEFFECTS

[Please note that, unless otherwise indicated, field strengths, currents, etc. are given in terms of the root-mean-square (rms) value.]

Biophysical Principles of Coupling to the Electric or Magnetic Field

The following paragraphs summarize the most important biophysical principles affecting the strength and location of bodily electric fields, this "coupling" of the field to the organism and the tissues therein bears importantly on interpretation of the research findings.

§ The human or animal body acts like a conductor at 60 Hz. The external electric field is strongly concentrated at curved surfaces of the body resulting in strong enhancements over the field that would exist if there were no body present (the "incident field"), e.g., at the top of the head where an incident field of 10 kV/m results in a surface field of 180 kV/m (Deno, 1977). The internal field is very much weaker than the external field, e.g., for typical conditions during exposure to an incident 10 kV/m (10,000 volts per meter) 60 Hz electric field, the field within the human chest is about 0.02 V/m (Kaune and Phillips, 1980). It is certain that electric fields in air can not induce body currents great enough to be a primary shock hazard in the sense that touching a live wire produces strong currents in the body (Schwan, 1972; Deno, 1977; Schneider et al., 1974).

§ Within the body the quantities of theoretical interest are the current density and the associated internal electric field. The anatomical complexity of the interior of the body has so far frustrated confident analysis of precise interior current densities (Sheppard and Eisenbud, 1977, Kaune and Phillips, 1980) thereby impeding efforts to determine the mechanisms of electric field interaction.

§ Excepting special tissues bearing that bear permanently magnetic materials, it is doubtful that a purely magnetic interaction occurs in biological tissue (Sheppard and Eisenbud, 1977), and the effects achieved with magnetic fields are probably entirely due to induced electric currents whose magnitude is determined by the effective radius of the current path, the frequency and intensity of the magnetic field. Magnetically-induced electric currents are greatest at the periphery of the body where the conducting paths are largest.

§ No animal model successfully mimics human exposure conditions. At best, a single experiment can approximate human exposures according to either the surface fields at a selected spot, or according to internal current density at a selected organ (Kaune and Phillips, 1980). This makes extrapolation of animal test results to humans difficult until the site of interaction is known.

§ Comparisons within a species or between species are strongly affected by orientation as well as body shape. The data indicate approximate equivalence of internal current densities and surface fields when a grounded rodent is exposed to at least 5 to 20 times the field strength of a grounded human (Barnes et al., 1967; Sheppard and Eisenbud, 1977; Kaune and Phillips, 1980). For this reason, if experiments with rodents show a biological effect, the same effect may appear in humans in a field strength 1/5 to 1/20 as strong, assuming equivalence of the purely biological factors.

§ Kaune (1981) presents data to show that in a 50 kV/m field (60 Hz, unperturbed) the resting, grounded rat has a maximum electric field (at the back) equivalent to that at the top of the human head for a person in a 10 kV/m field. For these same fields, current densities at most portions of the human will often exceed those in the rat, but will often be within about a factor of two (Kaune and Phillips, 1980).

STUDIES with HUMAN SUBJECTS

A number of studies has been conducted among utility workers exposed to strong electric fields during the course of work in substations, or as linemen. Recent data (e.g., Male et al., 1982) indicate that linemen are exposed only sproadically to strong fields, while some substation workers have higher time-averaged levels of exposure. There are also a few laboratory studies of physiologic responses to acute exposure to strong electric fields and a some data on field perception, levels of annoyance and response to spark discharges. The third source of information comes from a limited, but growing list of epidemiologic studies that involve either the general population or persons in particular occupations that may involve greater than average exposure to electric and/or magnetic fields.

Initial reports of health problems related to ac electric fields came from the USSR about 10 years ago (Asanova and Rakov, 1966; Korobkova et al., 1972) where research begun in the mid-1960s disclosed a syndrome of neurophysiologic complaints among workers in a 500 kV switchyard. In the USSR, such switchyards had electric field strengths up to about 14 kV/m with an estimated average field strength of about 8 to 10 kV/m (Sheppard and Eisenbud, 1977). A similar experience was reported among Spanish switchyard workers (Fole, 1972), but not elsewhere in the world including extensive investigations among switchyard workers in Canada and Germany (Stopps et al., 1979; Roberge, 1976; Bauchinger et al., 1981) and linemen in the USA and Canada (Kouwenhoven et al., 1967; Singewald et al., 1972; Stopps et al., 1979). In Sweden chromosomal abnormalities were found more frequently among switchyard workers as compared to other employees, but the data are not conclusive (Nordstrom et al., 1981). The Swedish investigations also present evidence for an increased rate of stillborn or deformed children and for an unusually low boy/girl ratio among the offspring of substation workers (Knave et al., undated; Nordstrom et al., 1981). In view of the interest generated by findings of apparent genetic changes among these workers, and in view of the observation of effects so far only among Swedish workers, further studies are required to address the issue with both epidemiologic and laboratory efforts. A Swedish study (Hansson Mild et al., 1982) shows that under laboratory conditions, strong electric discharge shocks can produce chromosomal changes, but the relevance to exposures *in vivo* is uncertain. The role of spark discharges as a primary or secondary influence in each of the foregoing surveys remains speculative, but it should be noted that in the USSR the imposition of work rules to limit spark discharge effects and to limit exposure above 5 kV/m apparently eliminated the occurence of the neurophysiologic symptoms (Bourgsdorf, 1975).

A survey among persons living in proximity to transmission lines in France showed that the consumption of health services and medication was apparently unrelated to proximity to the line (Strumza, 1970).

Considerable controversy surrounds other epidemiologic studies that show a correlation between low-voltage wiring configurations, and other indicators of magnetic field exposure with the incidence of certain cancers in Colorado children (Wertheimer and Leeper, 1979) and adults (Wertheimer and Leeper, 1982). However, a similar study (Fulton et al., 1980) found no such correlation among a group of Rhode Islanders. It is postulated that the magnetic fields associated with the wiring configurations are likely causative agents. The magnetic field strength at which excess cancers may occur according to the studies by Wertheimer and Leeper is about 5 milligauss (mG), as compared to the earth's static field of about 500 mG, or the HVTL-associated fields that range from 300 mG at ground level beneath the conductors to 10 mG at about 60 m from the transmission line. Much greater magnetic fields of several gauss are commonly found near household appliances and industrial machines, however in those situations exposure durations would probably not be long in comparison with residential ambient fields.

More recently, brief notes indicate that there may be an excess of cancers for occupations that presumably involve greater than average exposure to electric and magnetic fields (Milham, 1982; Wright et al., 1982).

Data were obtained from over 100 human subjects exposed to electric fields of up to 20 kV/m (50 Hz) for several periods during a series of three hour study sessions. No physiologic changes were observed in tests of the cardiovascular system and in recordings of brain waves, but changes were seen in some red and white blood cell counts (Hauf, 1974; Hauf, 1976. Behavioral changes were absent (Johansson et al., 1973) and a 200 uA conduction current, or a combined exposure to electric and a magnetic field also had no effects.

A medical survey of employees exposed to the weak electric and magnetic fields of a test transmitter utilized for the Project Sanguine/Seafarer communications system disclosed no exposure-related health effects (Krumpe and Tockman, 1972, 1974).

Persons can perceive electric fields (by the effect on hairs at the back of the hand) at levels as low as 1 kV/m under certain circumstances. A median perception level of 7 kV/m has been determined in one test of a large number of subjects (Deno and Zaffanella, 1982). Thresholds for annoyance as low as 5 kV/m occur, but the median value is very much greater than 20 kV/m, the highest value tested. Spark discharges are generally distasteful (e.g., Deno and Zaffanella, 1975). Some persons can perceive spark discharges to the finger or ankle in fields below 1 kV/m, although the median level of perception has a threshold at 2.7 kV/m (Deno and Zaffanella, 1982). Preliminary data exist to quantify reactions to particular shock energies (Hylten-Cavallius, 1975; Takagi and Muto, 1971; Krivova, 1975), but additional work, some of which is in progress (Reilly and Larkin, 1981), is required. Human perception of magnetic fields has not been demonstrated (Schmitt and Tucker, 1973).

RESULTS of ANIMAL RESEARCH

Recent research is reviewed against the background of past research that presented a highly uncertain picture in which few data of uncontested value were known. In contrast, there is now an emerging basis for the conclusion that 60 Hz electric fields of the magnitude found generally in the environment of HVTL lines, and perhaps even at much lower field strengths typical of some aspects of the home environment, can interact with a biological system in a reproducible fashion. It should be stressed that none of the better-documented bioeffects is accompanied by a pathologic condition in the test animals.

The extensive testing in animals already conducted permits confidence in the conclusion that exposure to electric fields does not result in a recognized disease or abnormal physiological or behavioral syndrome. If there were such effects they should have been seen in some of the many studies now complete. However, abnormal growth and development, and chromosomal changes have been recently observed among wild rabbits, a species not usually used in the laboratory and for which further evaluation of the preliminary data is needed (see section 5, below).

1. Animal Behavior Studies

There is now certain evidence for perception of 60 Hz electric fields by rats at field strengths below 10 kV/m and for which a "threshold" is set at approximately 7 to 8 kV/m, although individual rats perceive fields as low as 4 kV/m (Stern and Laties, 1981; Sagan, 1981). There is clear evidence from a number of behavioral tests that rats show aversion to the field under some circumstances at field strengths above 50 kV/m, and that they prefer to be exposed to a 25 kV/m field rather than to be in a shielded region, but only during the inactive phase of their daily cycle (Hjersen et al., 1980; Lovely, 1981; Lovely, 1982). Other behavioral changes in the rat seem to be observed at field strengths as low as 1.8 kV/m and independent of whether the animals are grounded or floating (Lovely, 1982).

Among the several investigators, different behavioral testing procedures have been employed, and important differences in the exposure apparatus also exist insofar as some work is with grounded rats and other work is with electrically floating animals. Nonetheless the extent of agreement among the researchers is remarkable.

A mechanism for these changes has not been elucidated. Although sensory perception as a result of electro-mechanical stimulation of body hairs or vibrissae (whiskers) is possible, studies performed with hairless rats (either clipped or a nude strain) indicate that these animals perceive the electric field at about the same field strength as the normal rats (Stern and Laties, 1981; Stern and Laties, 1982). Furthermore, electromechanical effects on hair have not been visualized at unperturbed field strengths of the order of 7 kV/m in rats. At 1.8 kV/m, the weakest field at which behavioral effects are reported, it is unlikely that hair vibration is an adequate stimulus.

None of the behavioral effects involves pathological changes in physiologic status, nor is behavior "abnormal". However, until the mechanism of interaction is better understood the behavioral data must be interpreted as evidence for the biologic potency of 60 Hz electric fields, without judgment on possible effects on the health of the organism.

Because of the well-known difficulties in scaling from small animals to humans, the electric field values just quoted for rats may represent human exposure to fields of the same, one-third, one-tenth or even far lesser field strengths as compared to those used in the rat studies. (As is usual, it is assumed that human responses would involve the same ultimate biological mechanism and so the human response could be predicted if the electric field or electric current density in man and rat at the appropriate site were matched.) The choice of a properly scaled electric field depends upon either (1) assumption that transduction is at a site on the rat where the surface electric field is about equal to the surface field at that site on the human body (but this is not reasonable everywhere, e.g., at the head where human fields are so much enhanced); or (2) assumption of transduction at the site of maximum rat body surface field which is about 1/3 the strength found for humans; or (3) assumption of transduction within the body by the effect of internal current densities, which in the rat tend to be about 1/10 or less the values for humans exposed to the same unperturbed field.

2. Animal Physiology Studies

A number of experimental results from *in vitro* studies show effects on tissue which are clearly due to the electric field action alone. The data obtained so far at relevant 60 Hz field strengths are limited, much work remains to be done to gain understanding of the mechanism of action, and exact scaling of *in vitro* exposure awaits more knowledge of current flow within tissues. Useful dosimetric comparisons can now be made but precise equivalence of *in vitro* and *in vivo* exposure is not now possible. For this reason, and because in some studies field strengths or current densities may greatly exceed those expected to exist within the human body under practical exposure conditions, it is not certain that the *in vitro* work exemplifies mechanisms that are also important *in vivo*.

Although limited in number, the data from laboratory exposed tissues and whole animals give clear evidence that an electric field biological effect is possible under conditions of exposure to HVTLs. None of the confirmed effects indicate a pathological change in the organism. At least one unconfirmed study involving rabbits exposed in a high voltage switchyard or in the laboratory does seem to show a pathological situation in certain brain cell structures.

Interpretation of the experimental data is subject to considerable latitude insofar as only a few field interactions have been well-characterized phenomenologically, and no electric field effect with a direct bearing on human health has been established.

The small magnitude of many statistically significant effects should be interpreted with an understanding of the adaptive capability of the organism (Michaelson, 1979). Adaptation to small changes ("stresses") may occur with no impact on health. For example, exercise or temperature changes produce effects on the body, but in the normal range of exercise or temperature, there is no harmful effect. In contrast, there may be profound implications attached to observation of small changes since the mechanism to transduce the field must involve an extreme degree of biological amplification of a very weak signal. For example, an allergen may have little effect on most persons, and even little initial effect on a sensitive person, but dynamic changes in the immune system can result in hypersensitivity, as occurs in a person allergic to penicillin or bee bites, etc. This suggests that if electric fields interact with an unstabilized aspect of the biological system, the long-term consequences of continued interactions could not be predicted.

3. Animal Health, Blood and Tissue Studies

Numerous studies of physiological parameters such as body weight, general health, blood cell populations, blood serum chemistry, plasma endocrine levels, histologic study of organs and tissues, reproductive capability, have been done (Knickerbocker et al., 1967; Marino et al., 1973a & b, 1974, 1976a,b & c; Noval et al., 1976; Mathewson et al., 1977; Quinlan et al., 1982; Blanchi et al., 1973a and 1973b; Seto et al., 1982a & b; Cerretelli et al., 1979;, Morris and Ragun, 1979; Morris and Phillips, 1982; Ragun et al., 1979, Sikov et al., 1979; Grisset, 1979; Dumanskiy et al., 1975; Rosenberg et al., 1981; Fam, 1980; and others). A few of these studies report physiologic effects in one or more areas. The importance of shock discharges or other collateral effects in some of the earlier studies (often showing significant effects) has been much discussed, but there is not yet clear evidence that shock discharges are responsible for any particular experimental results (Hilton et al., 1982). It is certainly true, however, that studies employing techniques that limit the secondary electrical effects to very low levels should be given greater weight when the effects of internal fields are at issue. The consensus drawn from the studies cited in the above listing is that there is no pattern of pathological effects among laboratory animals exposed for periods of several days to several months. Slight changes in blood cell counts occur in several studies and suggest that there may be an effect which has so far been seen inconsistently across experiments, including inconsistent results in replication studies. Strong preliminary evidence for effects on circadian rhythms has been presented (Duffy and Ehret, 1982), and some evidence for an endocrine effect exists (Free et al., 1981).

Some of the above cited studies report significant effects, while under nearly identical exposure conditions other researchers found no effects. This situation is not unique to electric field studies and may reflect differences in instrumentation, protocol or species, or improper techniques in exposure and handling of animals and statistics techniques, or in unobserved artifacts.

When so many studies are available, one can be confident that no pathologic condition occurs with a high rate of incidence and therefore conclude that these laboratory exposures generally reflect the benign nature of electric field exposure.

This conclusion does not mean that a person exposed to electric fields is "safe." The reasons for continued caution are: (1) The dosimetric difficulties indicate that animal experiments do not adequately mimic human exposures. Unlike chemical toxicology where exposure of a few animals to very strong concentrations of a substance can produce results believed to be useful in establishing safe limits for a general population of many individuals, the very strongest electric field exposure possible with laboratory rats would not exceed some aspects of human exposure by even a factor of two or three. (2) Experiments with strong electric fields, as used for most of the above studies, may not represent a complete investigation of the problem. Windowed amplitude responses occur in one class of *in vitro* studies, wherein a *reduction* of the field strength by a factor of 2 or 3 does not reduce the field effect, but causes a *greater* effect. This precludes a presumption that because null effects were seen during a test, null effects would occur if the test were conducted at a lower field strength.

4. Function of Nerve Cells

Neurophysiological data seem to establish the principle that weak internal electric fields can have effects on components of the nervous system including individual neurons, synaptic transmission in nerve fibers, and perhaps biochemical properties of the pineal gland. These results were obtained in experiments on small animals exposed to effective electric fields of 39 or 65 kV/m in air. Jaffe et al., (1981) has documented a change in the C-T ratio response that shows increased excitability in synaptic function of nervous tissue taken from rats exposed for 30 days to a 100 kV/m (effectively 65 kV/m) electric field. Other functional tests of the tissue showed no field effect. Wilson et al., (1982) and Anderson and Hilton, (1982) showed significant alterations in the concentrations of melatonin and SNAT in the rat pineal gland following exposure to 65 kV/m (39 kV/m effectively) electric fields. Preliminary reports (Jaffe, 1982; Anderson, 1982) indicate that these effects are also observable when animals are exposed to 1.8 kV/m.

5. Motor Function, Growth and Development, Cytoskeletal Changes

Research in Sweden found that rabbits exposed to the 14 kV/m field of a 400 kV (50 Hz) substation (Hansson, 1981a; (Hansson, 1981b; Hansson, 1982) showed large deleterious changes in motor functions, growth and development, changes in the cytoskeleton of brain cells, and alterations in the concentration of two glial proteins (S-100, GFA). The changes seen in Purkinje nerve cells of the cerebellum included abnormal internal cellular structures (endoplasmic reticulum altered to form lamellar bodies), reductions or absence of internal organelles and structures (certain mitochondria and hypolemmal cisterns), and reduced arborization of the dendritic branches. In laboratory exposures of rabbits to a 14 kV/m field the above cellular changes were found, but not the motor, growth and developmental changes (Hansson, 1982). Further research and confirmatory studies are needed to evaluate this evidence for a selective effect in brain tissue.

6. Calcium Efflux in Brain Tissues

A number of in vitro studies and one in vivo study introduce ELF fields to isolated tissue (Bawin et al., 1975, Bawin et al., 1976; Bawin et al., 1978a; Adey et al., 1982; Blackman et al., 1982; Lin-Liu and Adey, 1982; Dutta et al., 1982; Shelton et al., 1982; Merritt et al., 1982) by either of two techniques. These studies show an effect of ELF electric fields on the binding of calcium to the surface of cat and chick brain tissues or cultured tumor cells. Studies with weak extremely low frequency (ELF) fields (less than 100 V/m) applied to brain tissues in air, and with radio frequency fields modulated at ELF, show similar but not identical effects that include a windowed dependence on field strength. This indicates a possible major complication in studies of the electric field influence, especially if the windowing is specific to each tissue studied. The importance of calcium to many brain processes makes these findings of significance as a lead to a mechanism that may occur at the level of molecular binding to the cell membrane surface.

7. Neurophysiologic Studies

Wachtel (1979), Sheppard et al., (1980) and Bawin et al., (1981) present preliminary evidence from in vitro studies that electric currents alter excitability of neurons in a manner that interferes with pacemaker activity of invertebrate neurons or produces a long-term alteration in the electrical response elicited from brain cells of the rat hippocampus. These studies are conducted at current densities greater than those found in the tissues of field exposed animals or humans, but in some cases the tissue electric fields are similar. The results do not show that the tissues have been harmed, although functional changes occur. If these studies involve a mechanism significant at lower current densities, or if the mechanism is best measured by electric field strength rather than current density, the results found at the tested field levels may apply to HVTL exposure conditions.

I SCOPE and PRINCIPAL ISSUES

The purpose of this document is to provide information to the Montana Department of Natural Resources and Conservation on the biological effects and possible health effects of 60 Hz electric fields produced by electric power transmission lines. This information is required to assess the occupational and public health significance of exposures to 60 Hz fields that would result from operation of the high voltage ac transmission lines of the Colstrip Power Project, and to indicate areas in which health hazards may be apparent.

To achieve this purpose, the scientific literature on biological interactions with extremely low frequency (ELF) electric fields is critically reviewed with respect to its adequacy in establishing the nature of such effects, their physiological significance, and the possible health effects in humans.

In order to provide the most meaningful review of the relevant literature, data on biological effects in animals exposed to electric fields at frequencies above zero and up to 100 Hz or more are included, although the transmission line exposure will be almost exclusively at 60 Hz. The data of effects at ELF predominantly involve electric field exposures only, but some relevant data involve alternating magnetic fields. Electrostatic and magnetostatic fields of dc transmission lines are not discussed herein, but are the focus of a companion document. The waveforms considered are predominantly sinusoidal, but some experiments involving pulsed fields are discussed.

1. Exposure in the Transmission Line, Home and Natural Environments

The natural electric fields at ELF are very weak, and by far the largest fields are those of man-made origin. The strongest environmental 60 Hz electric fields are those that surround high voltage transmission lines.

Numerous calculations and field measurements exist to indicate the precise electric field patterns that occur for particular transmission lines, and the data of table 4.9 of the BPA Draft Environmental Impact Statement (Department of Energy, 1982) indicate that the proposed Colstrip Project Transmission Line is typical of other high voltage lines that produce a maximum electric field of about 10^4 volts per meter (V/m) at the point of lowest ground clearance, at a distance from the centerline that is slightly outside the outer conductor. The 9 kV/m electric field strength listed for both the single and double circuit lines of the Colstrip Project would not occur except where the line achieves maximum sag (at midspan, at time of highest conductor temperature, as influenced by air temperature and the current carried by the line). Moving away from the transmission line in a perpendicular direction the electric field falls off to the background level of 10^{-4} V/m at approximately 10^3 meters (m) (Sheppard and Eisenbud, 1977).

Within the home the proximity of appliances and low voltage wiring produces electric fields of 10^{-1} to 10^2 V/m (Sheppard and Eisenbud, 1977).

By contrast with the man-made electric fields, the natural electric field at 60 Hz is about 10^{-4} V/m, about 10^{-5} times the magnitude of the fields introduced into home by wiring or appliances and about 10^{-8} times that of the maximum transmission line fields. Unless there is an interaction between biological systems and HVTL 60 Hz electric fields this sharp change in the natural environment is not necessarily indicative of any impact on living organisms.

Apart from an investigation of effects attributable to a direct action of the electric field, collateral effects such as shocks produced by transient discharges of objects energized within the field, and interference with cardiac pacemakers require consideration in order to establish regulatory standards in consideration of all possible modes of influence on human beings.

2. Exposure Conditions in the Laboratory

Because the coupling between objects and the field is strongly dependent on shape and orientation, laboratory experiments with animals can not accurately simulate exposure to humans (Kaune, 1981; Kaune and Gillis, 1981). In general, electric field strengths that exceed the HVTL fields by a factor of 5 to 10 are required in animal studies to produce electrically equivalent exposures within the bodies of a human and a laboratory animal. Lesser extremes of exposure to the laboratory animal are required to produce equivalent effective surface fields in the two species. For these reasons it is necessary to consider the results of laboratory experimentation in electric fields of 10^5 V/m, and larger.

In contast with the strong electric fields that must be produced in air to simulate human exposure in the laboratory, studies with excised tissues exposed to an electric field *in vitro* must use electric fields in a conductive liquid medium that are approximately 10^{-2} V/m (100 uV/cm).

The ratio of about 10^6 between the electric field in air and the tissue-level fields is a reflection of the poor coupling between the field in air and tissue for all organisms.

3. Electric Field Measurement Instruments and Techniques

Measurements of the free-field transmission line electric field (no objects present) can be accurately made using commercially available instrumentation. Accurate measurements of laboratory exposures is often more difficult because of the size of the electric field probes available, although small probes of small diameter have been successfully designed and used (Misakian et al., 1978). Of course, accurate measurements in both the laboratory and HVTL regions require caution and experience. Several published reports in the engineering literature are available for reference to the the techniques by which reliable, calibrated measurements may be made (Barthold et al., 1971; Deno and Zaffanella, 1975, Lambdin, 1978; Tell et al., 1977; Bracken, 1976; Shih et al., 1977). In general, the design parameters of the transmission line and local terrain will determine the ground level electric fields that occur, but it is not generally required to make extensive measurements to ensure compliance with design specifications.

GOALS of this DOCUMENT

This document is prepared in order to assist in a determination of a suitable regulatory standard for design and operation of the Colstrip Project Transmission Line (CPTL) within Montana. The principal issue is the determination of electric field strengths that would be considered as

1. Safe under all circumstances.
2. Hazardous under certain circumstances.
3. Hazardous under all circumstances.

Insofar as electric field strength falls off rapidly with distance from the line, these broad categories would easily translate into distances from the line at which the above categories of hazard would be defined, and be used to define required widths for the right of way. Although the present extent of scientific knowledge of the effects of 60 Hz electric field does not permit unequivocal determination of any of the above categories, it is the goal of this document to establish criteria that indicate those electric field strengths to which the public can be exposed with a very high degree of confidence that health is not adversely affected.

1. Classes of Exposure to Humans

The practically ocurring situations of electric field exposure involve both acute and chronic durations. Acute conditions of exposure to the strongest electric fields occur for exposure within the right of way (ROW), such as occur on occasion of farming or ranching activities, recreational use of the ROW, or at road crossings. More continual exposure to weaker fields occurs in the case of a workplace, recreational site or home located adjacent to the ROW.

2. The Basic Scientific Issues

The deterimination of suitable electric fields exposure standards is based upon the available scientific literature including epidemiologic data for humans, physiological data from exposed persons and from animals exposed in the laboratory, and from a consideration of the basic mechanisms of interaction. Two classes of mechanism must be considered. One is the study on a macroscopic scale of the electrical properties of biological systems, and the second is a study on a microscopic scale of the organization of biomolecular systems that may account for the interaction of ELF fields with biological systems. The biophysical considerations allow quantitative study of the currents and fields within the body or at its surface, while the theoretical cosiderations allow speculation on the nature of the interaction, its implications and likely significance.

Taken together with the biophysical data, an understanding of biological tissues and the information processing functions of the nervous system, make it possible to discuss the electric field influence in quantitative terms. Thus, within broad limits, it is possible to compare the influence of environmentally imposed electric fields with that of normally occurring, biologically-derived electric fields and currents.

The focus of the controversy over weak electric field effects is the determination of the lower threshold for significant field effect. One approach to such a threshold would be from a study of the levels of physiologically important naturally occurring electric fields and their frequency spectrum. At this time little guidance is available from this consideration because the range and significance of naturally occuring fields e.g., within the brain, have not been determined. An alternative approach to the influence of weak environemntal fields would be by study of the range and frequency spectrum of environmental fields of known physiological importance. For humans, no such fields are known, and for a few animal species this question is still undergoing study preliminary study that cannot provide a direct response to questions concerned with effects in humans.

3. Social and Scientific Issues

The regulation of a device which has social effects as broad as those of an electric power transmission line involves many issues that require scientific input or scientific literacy, but which are essentially issues for which the society at large must establish the scale of values. Electric power transmission touches on issues of energy policy, land use, state power over private property, economic well-being, aesthetics, impact of modern technological devices on rural lands and the alterations in physical environment due to noise, electric and magnetic fields, soil compaction or erosion, etc.

It would appear that the issue of "health hazard" of electric and magnetic fields should be capable of a relatively narrow definition. However, faced with the same facts one group has determined that enough is now known to conclude that there is no demonstrated hazard, and therefore the line is "safe" (e.g. Miller and Kaufman, 1978). In contrast, others find that the facts show that little is known, particularly about the biological interactions, so that biological hazards would be presumed possible or even likely, unless demonstrated otherwise (e.g. Marino et al., 1979).

Often, this controversy revolves about the distinction between "effect" and "hazard". It is clear that demonstration of a bio-effect is not equivalent to demonstration of a health hazard, but when relatively little is known about the basis of the bio-effect different persons may come to opposite conclusions on the likelihood of a deleterious health effect. For example, fluoridated water has a beneficial bio-effect on teeth with little associated hazard, coffee has obvious biological effects, including promotion of chromosomal changes, but in moderate amounts is not considered hazardous, and changes in climate affect the body, without any necessary hazard. On the other hand, low levels of ionizing radiation have no certain bio-effect, but the degree of hazard is highly controversial.

It is an important goal of this report to take this fundamental problem into account. The hazard vs effect controversy exists in many regulatory cases, but is more emphasized here because of the potential for effects on the information processing function of cells, particularly those of the central nervous system, via interactions that are outside the scope of past experiences with toxicologic agents.

The recommendations of this report are formulated in explitt recognition of the distinction between hazard and effect, and with recognition that the potential for effects is distinct from a demonstration of such effects. However, based upon the spectrum of results that are reviewed, my recommendations take into account the range of bio-effects and suggest an electric field level that prudently reflects concern for the existence of subtle electric field effects that represent a risk to the well being of human beings.

4. What Constitutes Safety?

It is well known that safety is a relative quantity since absolute safety cannot be assured for almost any technological device. The usual formulation of this point of view is in a consideration of risk versus benefit, so that where little benefit is apparent there is little justification for even slight risks, whereas some risk is justified by the appearance of substantial benefits.

Whatever the merits of the attempts to quantify risk and benefit for electric power transmission lines and their associated electric fields, at this time no such analysis could be of quantitative assistance in setting a criterion for electric field strengths (but, q.v., Rish and Morgan, 1979). At the least, there are no data that permit quantitative estimation of a loss in health due to operation of the line.

Also, there are no data that can prove the total absence of risk, for this is logically impossible as it requires total knowledge.

In this situation, the degree of safety can be estimated from past experience with electric fields and a scientifically accurate and open-minded analysis of the nature of the biological interactions.

I attempt to establish a level of safety that recognizes these significant aspects of exposure to the the transmission line electric field:

1) Exposed persons are potentially "at risk" for many years.

2) Exposed persons are apart of the general population and will include old, young, healthy and infirm individuals.

3) Biological response to the same agent can vary widely among individuals and some subset of the population may constitute a sensitive population. No criteria exist to identify such a group. In like manner, certain tissues or organs may have greater sensitivity to electric fields. There is a presumption that the nervous system in general, or particular parts of the brain, should be identified as sensitive targets.

4) A relatively small fraction of the total population is exposed, so that infrequent effects might not be noticed, even with suitable epidemiologic tools.

5) Biologic systems are imperfectly understood.

6) Establishment of an unnecessarily strict electric field standard entails significant economic costs.

5. Topics Omitted from Detailed Consideration

This document is focused primarily on the effects of 60 Hz electric fields for which there is the greatest body of scientific research. Wherever electric currents flow there will be 60 Hz magnetic fields as well. Transmission line currents are variable, but generally never exceed 4000 Amperes at full load. Of the various sections of the Colstrip Project Transmission Line (CPTL), none would produce a magnetic field in excess of 0.5 Gauss (50 uT) at ground level. In theory, the magnetic field could act directly on magnetic materials or could act indirectly through the induction of an electric field within the body tissues. There is only scant evidence to suggest a role for direct magnetic field interaction in humans by extrapolation from magnetic field detection in other species, where it appears the geomagnetic field provides a clue used for navigation by several migratory species, including sharks, rays, dolphins (Kalmijn, 1971, 1974), birds (Wolcott, 1974; Wolcott et al., 1979), bees (Gould et al., 1978) and as a clue for an orientational response in certain bacteria (Blakemore, 1976; Frankel et al., 1979; Frankel and Blakemore, 1979). Attempts to demonstrate magnetic field receptivity in humans have not been successful, although controversy exists (Schmitt and Tucker, 1973).

A comparision of the magnitude of the indirect electric fields introduced into body tissues by an alternating magnetic field of a HVTL (Sheppard Eisenbud, 1977) indicates that their maximum magnitude is less than the magnitude of currents due directly to the electric field of the HVTL.

Often, the effects of magnetic fields are dismissed by a comparison of their magnitude with the geomagnetic field (0.5 G). This argument is flawed because it ignores the oscillatory character of the HVTL magnetic field, and because, in the absence of a strong electric field, the magnetic field may be examined for possible influences on biological systems. Controversy about the effects of extremely weak magnetic fields has been spurred with the publication of epidemiologic data that suggest a correlation between magnetic field exposure near the home and the incidence of cancer (Wertheimer and Leeper, 1979; Wertheimer and Leeper, 1982; Fulton et al., 1980; Milham, 1982; Wright et al., 1982).

At this time it appears that consideration of a possible magnetic field interaction near a high voltage ac transmission line is secondary in importance to consideration of electric field effects. This document does not treat magnetic field effects comprehensively, but insofar as a time-varying magnetic field introduces an electric field, some "magnetic field research" is relevant and is considered from this point of view.

Data have been obtained on the growth and productivity of trees, crops and laboratory plants during exposure to HVTL electric fields (McKee et al., 1978, 1982; Lee et al., 1979). The data suggest no important influence on plants, except that corona on leaf and needle tips can occur on trees within the ROW with the result of necrosis at the leaf tips.

Because the corona process generates gaseous products, of which ozone is likely to be the most harmful, there has been investigation of the amounts and concentrations of ozone produced by HVTLs under various corona conditions (Frydman et al., 1972; Roach et al., 1973; Frydman et al., 1973; Fern and Brabets, 1974). It is now clear that the level of oxidants produced by the line is not of concern as a health hazard and only rarely is an increase above ambient levels measurable near the line.

Issues of corona-generated noise, radio and television interference are not considered.

II FIELD INTERACTIONS with HUMANS and ANIMALS: BIOPHYSICAL CONCEPTS

1. A Definition of Electric Field

Although study of a treatise on the field concept in physics and engineering would require familiarity with sophisticated mathematical and physical ideas, the basic idea of the electric field as a convenient way in which to discuss the influences among charged materials should be clear to anyone concerned with the issues of this report.

An electric field is created wherever electrically charged matter is rearranged from equilibrium (neutral on an atomic scale). It can be said that the power station generator rearranges the electrons in the conductors in order to transmit electrical power. Commonly one refers to voltage as a measure of the energy associated with the excess (or deficit) of charge on an object. When two objects are at different voltages, the space between them is characterized by this voltage difference.

A potential difference is defined for that space on the basis of the work that can be done on a charge ("test charge") brought into the space. This work is performed "by the distant arrangement of charges", or in equivalent jargon, "by the electric field".

The essence is that in places where there is an electric field energy can be transferred to the charged parts of matter. Further discussion below shows that in the case of the 60 Hz HVTL the magnitude of the energy transferred to human or animal bodies is exceptionally small.

2. Transmission Line Electric Field

In the case of the ac transmission line, a conductor is raised to a high voltage with respect to ground and so the region between the conductor and ground is influenced by an electric field. Of course the primary purpose of the transmission line is to carry the energy to a distant point and not to lose too much energy by doing incidental work along the way.

The HVTL electric field is an inescapable aspect of overhead power transmission. It has become an issue because, at the field strengths required to provide economical bulk power transmission, the fields are intense as compared to either naturally occurring fields (see above) or to other manmade fields.

3. Energy Transfer by the Electric Field

When the field is strong enough, as occurs immediately adjacent to the wires, the field gives enough energy to the molecules of air for corona to occur with resultant noise, light, emission of radio noise and gaseous products.

Near ground, the electric field is weaker than it is adjacent to the conductor, and the coupling of the field to a human or animal body is exceedingly weak. The energy density introduced by a 10 kV/m electric field is approximately 4.4 10^{-8} joules/m^3, producing in man a power density of about 10 microwatts/m^3. This is about 10^{-8} times the metabolic heat rate of the human body (Sheppard and Eisenbud, 1977). There is no doubt that the amount of energy transferred (as heat) to a body is totally ignorable in comparison with normal metabolic heat production. This suggests that it is necessary to determine if there is a biologically important way in which to transfer an energy signal to the living system.

4. Electric Field Influence on the Body: Fields within the Body

The influence of the electric field may be examined in terms of an effect at the body surface, where hair or skin receptors of the sensory nervous system may act as biologic amplifiers to allow the organism to recognize the presence of the field. Or, in the event that effects occur within the body, it becomes important to know the electric fields within the body.

Although the human body has dielectric properties that are important on both the macroscopic and microscopic scales, the dominant characteristic of the body in a low frequency field is that of a conductor (Schwan, 1957, 1972, 1977; Barnes, et al., 1967; Sheppard and Eisenbud, 1977). Indeed, adequate models for the field outside the human body can be achieved with a metal foil-covered dummy (Zaffanella and Deno, 1978; Schneider, et al., 1974, Kaune, 1981, Gillis and Kaune, 1981).

Because the presence of the conducting body disturbs the field, the "unperturbed field" that is present before introduction of the body, is distinguished from the final "effective field".

At the surface of an electric conductor the electric field lines are perpendicular to the body. (These lines are just the directions along which a charged body moves in the field.) A curved conductor, such as the human head, has a greater concentration of electric field than exists on a flat plate or on less curved portions of the body. For this reason, it is necessary to specify the surface electric field that exists at a definite position on the body.

These surface fields have special importance in the evaluation of superficial sensory effects such as may be caused by hair vibration. But also, the conductor placed in an electric field carries a displacement current within it that is directly related to these surface fields. Thus, at the regions of most intense surface field the internal current densities that flow across the surface are greatest. The current flow through an object not connected by wires to a source of electricity, but instead coupled by its capacitance, is known as a displacement current. It is impossible, however for an electric field to induce displacement currents great enough to be hazardous as a live wire can be (Schwan, 1972, Deno, 1977; Schneider et al., 1974).

Models for interaction may assume effects proportional to current density, or proportional to electric field strength, so that different criteria would apply in tissues of different resistivity. Correspondingly, scaling would follow either internal electric current density or field strength. Two such models would characterize the ultimate biophysical interaction as either "voltmeter-like" or "ammeter-like". Whether an experimental result should be scaled according to current or electric field may be important because the tissue conductivity that relates these two quantities varies significantly among various tissues and even more widely among the tissues or subcellular components (e.g., plasma membranes) of different species and especially in studies performed *in vitro*.

5. Magnetic Induction of Electric Fields

Although the effects of environmental magnetic fields are beyond the scope of this document, the results of certain experiments with AC magnetic fields are relevant to an evaluation of the effects of electric fields since electric currents of similar frequency and magnitude flow in tissues exposed to magnetic fields or electric fields. Excepting special tissues that bear permanently magnetic materials, it is doubtful that a purely magnetic interaction occurs in biological tissue (Sheppard and Eisenbud, 1977). The magnetically-induced electric currents are greatest at the periphery of the body where the conducting paths are largest, whereas microscopic current loops defined anywhere within the body would have extremely small current densities. The magnitude of the current density is also influenced by the conductivity of the tissue and the exact paths for currents flow will depend in a complicated way on the conducting properties of tissues.

Thus, an evaluation of magnetic fields experiments for their relevance to an electric field exposure requires knowledge of the magnetic field strength, frequency or pulse rise time, and the dimensions of the conducting body (test tube or animal body) in order to determine the radius of the current loop for the tissue being studied. The isolated consideration of just one parameter, such as magnetic field strength, is without justification.

6. Capacitive Coupling to the Electric Field

In the laboratory the transmission line electric field environment is usually represented in idealized fashion by a pair of parallel metal plate-electrodes energized to a large potential difference. The unperturbed electric field between two such plates of infinite extent is given by the ratio of the potential difference and plate separation, e.g., a 5 kV (kilovolt) potential difference across 0.5 m, results in an unperturbed electric field of 10 kV/m. If the electrodes are horizontal, than the electric field will be vertical, the most common configuration, and one that represents the transmission line field fairly well although coupling of the horizontal rat to this field yields low axial currents in comparison with a horizontal field, which is rarely used (Marino et al., 1974). The actual transmission line field is composed of the sum of three fields that are 1/3 cycle apart and has horizontal field components.

An animal body is coupled to the electric field in proportion to its capacitance and the greater the capacitance the greater the current flow in the animal. Typically the capacitance of a rat is about 5 pF while humans have much larger bodies and typically a capacitance of about 125 pF when in close proximity to ground (Deno, 1977; Deno and Zaffanela, 1982). The capacitance, and thus the induced current, decrease for a body far from both ground and the energized electrode.

Overall, current densities will differ between fat and thin persons, between persons standing and reclining, and between persons walking barefoot and those with thick soled shoes or standing on a platform. In many small animal exposures the distance between the animal and the lower electrode is small or nonexistent so that the animal's capacitance to this lower (usually grounded) electrode represents a substantial portion of the total capacitance. Exposures of grounded and floating animals will be different, with less concentration of internal currents at the paws for the electrically floating animal (Sheppard and Eisenbud, 1977; Rosenberg et al., 1981).

7. Comparison of Exposures to Humans and Laboratory Animals

Exposures of an animal and a human being in a vertical electric field result in very different internal current densities and electric fields. Not only are the absolute magnitudes different, but the proportions are different. Thus, in principle it is possible to achieve an exposure of, for example, a rat thorax at the same magnitude as the human thorax, but the exposures to the head would be very different. There is no way to avoid the shape-dependent factors that influence internal currents. Similarly electric fields at the surface of the body can, in principle be adjusted to similar values for one position, but not for any general situation. And, achieving "parity" for a surface field condition would not result in "parity" for the current density to internal organs of two different animals.

No animal model successfully mimics human exposure conditions. At best, a single experiment can approximate human exposures according to either the surface fields at a selected spot, or according to internal current density at a selected organ (Kaune and Phillips, 1980).

Because the mouse and rat have similar body shapes, and because fields and current desnisites are independent of body size (Barnes et al, 1967; Gillis and Kaune, 1981), experiments at the same external electric field strength in these species result in equivalent bodily fields and current densities.

Tables and drawings from data developed by Kaune and Phillips (1980) provide information on the surface electric field at a few sites and for current density across particular sections of the human body, such as neck, chest, legs, ankles. These data can be compared for similar values in swine or rats at approximately similar body positions.

The data indicate approximate equivalence of internal current densities and surface fields when a grounded rodent is exposed to at least 5 to 20 times the field strength of a grounded human. For example, the current through the neck in a man exposed to a 10 kV/m field is 550 nA/cm^2, while in a 100 kV/m field the rat neck current is about one-half that, or 280 nA/cm^2. However, in those same fields, the human mid-thorax average axial current density is 190 nA/cm^2, and the rat has a thorax current density of 160 nA/cm^2 near the neck, but only 20 nA/cm^2 near the hind quarters. Comparisons within a species or between species are strongly affected by orientation as well as body shape. The total net current in a horizontal rat exposed to a 10 kV/m vertical E-field is 0.25 uA, but when the rat rears that current increases five-fold to 1.3 uA. Kaune and Phillips suggest a 20 to 1 ratio for axial current densities between man and the horizontal rat, and a ratio of 3.9 to 1 between the neck current densities of man and a rearing rat.

Precise calculations for current density in the human brain have not been reported, but in a 10 kV/m vertical electric field at 60 Hz this current density can be expected to be of the order of 100 nA/cm^2 (my calculation). (C.f., the value of 60 nA/cm^2 at the top of the head cited by Kaune and Phillips, [1980].)

On the basis of the estimated brain current density of about 100 nA/cm^2 in man, an equivalent field strength for the rat would be less than the field strength obtained by scaling from other factors (such as maximum current density), and would lie in the range of 20 to 60 kV/m, allowing for uncertain understanding of currents in the rat brain (my estimate). Kaune (1981) cites 49 kV/m for an equivalent field strength for the resting, grounded rat when scaled according to the maximum electric field at the head, in agreement with the previous estimates.

Another approach to the determination of relative exposures between man and animals is to determine the so called "enhancement factors" for the surface electric field near the body. Deno (1977) reports that for humans the surface electric field at the top of the head is 18 times that of the unperturbed electric field whereas at the back of the head the enhancement is 15 times while at the upper arm an 8-fold enhancement occurs for the size and shape parameters given by Deno. Deno (1977) presents other useful "rules of thumb".

More recent data (Kaune, 1982) indicate that the maximal internal currents in man occur near the armpit where large horizontal components of the current density are found.

Computer models of current flow in the baboon have been developed by Spiegel (1977) and Cahoon (1982).

8. Shielding in Multi-Animal Experiments

In many experiments, rodents are housed several to a cage. As a result of their proximity there is considerable mutual shielding which has been measured to yield a time averaged reduction in effective electric field strength of 35% (Free et al., 1981). Further development of this dosimetric data base will be crucial to further understanding of how to scale from animal studies to humans.

9. Harmonic Distortion

Because of the very high impedances in a typical transformer-driven high voltage electrode system, it is likely the harmonics of the 50/60 Hz line frequency will be significantly present in the electric field unless special care is taken to filter the input current and to choose load impedances on the transformer that do not support resonances at the harmonic frequencies (Phillips, et al., 1978). Such harmonics can compromise an investigation because the internal current density is proportional to the frequency and thus the third harmonic will be amplified three-fold over the fundamental, so that a seemingly low level harmonic content (say 10 percent) becomes a large fraction of the internal current density.

10. Hair Stimulation

In strong electric fields hair can be set into oscillation by the electrostatic forces on the hairs and the movement of hairs on the ear tips of swine has been detected photographically in strong electric fields of 50 kV/m (Phillips, et al., 1976), but not observed at 80 kV/m for rats (Phillips and Kaune, 1977). It is possible that small hair movements that are within the range of sensory detection could occur without observable hair oscillation. The interpretation of animal experiments conducted at elevated field strengths above approximately 10 kV/m is made difficult because animals chronically affected by this sensation might demonstrate a physiological or behavioral response to the stress caused by continued stimulation, or they might show alerting responses when the field is energized. Only the use of truly hairless animals or application of conductive lotions to the fur could eliminate these problems, but would introduce additional serious difficulties to the experiment. Because of the possible contamination of data from small animal experiments at high field strength by weak sensory events at the skin, it becomes important to conduct a balanced mixture of studies on animals of different sizes and shapes so that surface-field dependent effects such as these can be distinguished from current density-dependent effects that scale differently with animal size and shape.

III REVIEW of the BIOEFFECTS LITERATURE

Guidelines to Interpretation of the Data

Before engaging in detailed review of the most important data it is useful to consider a few of the attitudes one might find upon examination of other reviews of this literature. The reader who senses the appropriateness of each of the following points of view will appreciate the sophistication that must be brought to bear when scrutinizing a scientific area in which only the first steps have been taken, and when these steps are somewhat off the well-established paths developed for other environmental and scientific issues.

At present, understanding of the extent of the biological effects of weak electric and magnetic fields is limited by several factors. These include the existence of credible, but seemingly inexplicable data for a few phenomena of unknown significance for human health, the absence of an established field-related pathologic condition, little cross-linking of the biological systems in which effects have so far been seen, inadequate theoretical understanding of the physical or biological basis for an interaction, and some circumstantial evidence for effects on cellular genetic material. In this situation it is possible to conclude that there cannot be much of a practical problem with an agent that, at the strongest levels does not produce a recognized pathological condition. To the contrary, it is also possible to conclude that the potential for harmful effects cannot be evaluated, especially when fundamental cellular processes or behavioral activities are modified by the fields at low levels. The point of view adopted in this document is that a balanced overview of the established bioeffects and of less certain bioeffects recommends caution until the experimental and theoretical issues are clarified and until the full implications of the effects are evaluated.

One important aspect of the conflicts is that the existing biological and physical theories can not explain the phenomena observed so far. This event requires that either new theoretical ideas be developed, or the presumed relationship between the electric or magnetic field and the phenomena must be questioned. The inevitable reluctance to consider established ideas inadequate until the phenomena that make such reevaluation necessary are well established means that there is likely to be considerable controversy in the future. This controversy is a part of the scientific process by which ideas are developed and it is not merely an indication that present scientific knowledge is inadequate.

In the case of transmission line electric field issues, the adequacy of current knowledge was a prominent issue at the hearings on health and safety issues related to a 765 kV transmission line in New York (Scott-Walton, 1979). Prominent scientists testified that there was an established biophysical theory by which electric field interactions could be adequately understood, that this understanding showed there could be no physiologically significant effects on body cells, and that the phenomena were so poorly established that they did not create a need to reevaluate the theory. Since that time, there have been substantial advances in establishing the phenomena, and in the view of this report the New York State Administrative Law Judges (Colbeth and Matias, 1978) and the Public Service Commission (New York PSC, 1978) were reasonable in exercising the cautious approach that required an expanded right of way pending resolution of the health and safety issues.

In the scientific method the resolution of divergent points of view depends upon experiments that probe particular hypotheses. The final result is that either the established principles will hold or new ones will be needed. Intelligent analyses of the situation can clarify the extent to which certain phenomena are understood and the degree of theoretical understanding that exists, but such analyses cannot short-circuit the scientific process. For this reason, until evidence is clearly established and appropriate theoretical understanding is obtained, it is certain that some scientists will skeptically conclude that the data are insufficient to warrant serious consideration of the contradictory evidence. These skeptics may expect that all the seemingly aberrant data will be found to have classically founded explanations, or be classed as experimental errors, as sometimes happens when established ideas are challenged by seemingly revolutionary data. However, if the data establish the reality of the phenomena, attention turns to attempts to accommodate the data on a theoretical basis.

In the present situation there are some phenomena that cannot be explained by accepted biophysical or biological theory. The bulk of this report examines these in some detail, which is necessary because not all experiments are equally applicable to the HVTL issue when it is defined in terms of environmental 60 Hz electric fields of about 1 to 10 kV/m and 60 Hz magnetic flux densities of 10-500 milligauss (mG).

In many other environmental problems, much can be learned from experiments conducted at doses ten, one hundred, or more times the relevant environmental rate. Evaluation of electric field effects at high field strength is hampered by the increasingly troublesome role of secondary effects and by the limitations presented by well known electric shock current effects. Thus, experiments must be done at field strengths within about 10 times the HVTL maximum field strength. Moreover, extrapolation from high field strength experiments with animals is difficult for reasons discussed previously (section II).

The debate over biological interactions with fields, and more pointedly, debate on the possible health effects of the established interactions, has already been joined, especially as it pertains to transmission line electric fields. Partisans of one point of view or another have emerged, but the scientific positions have yet to be defined well enough to describe the character and extent of human physiological and behavioral response to electric fields -- or to establish the absence of such effects under conditions of chronic exposure at various field strengths.

It follows that socially important decisions that result in an assessment of the risk to health must be made without scientific consensus on many important topics. While this situation may appear bleak, it is the purpose of this report to suggest an interpretation of the existing data and their possible theoretical bases that can be a practical guide to public policy on the practices of electric power transmission via overhead conductors.

Interpretation of the experimental data with respect to health hazards is subject to considerable latitude insofar as few field interactions have been well-characterized and no electric field effect with a direct bearing on human health has been established. For this reason, when different reviewers consider studies that demonstrate no field effect, some view a null or weak effect as additional evidence for the essentially benign nature of the weak internal electric fields, while others may speculate on potential effects, especially if other biological and physical parameters had been used and other biological variables had been studied.

In like manner, the small magnitude of the statistically significant effects found for many positive effects leads some reviewers to emphasize the physiological insignificance of small changes, while others emphasize the profound implications of any such alteration. Since the mechanism for effects must involve an extreme degree of biological amplification, the interaction may involve an important biological system for which the long-term consequences of continued interaction might not be readily apparent.

A method by which these opposing points of view may be resolved, if only partially, is to draw the strongest possible conclusion from the uncontested portions of each argument and to eschew all but the essential conflicts that might bear on health. In face of these essential conflicts, judgments can be made using the conservative results that follow from the assumption of a worst case example.

Except under conditions where a particular mechanism is under investigation and where done in an artifact-free manner, experiments show a correlation of "effect" with the field exposure, but do not show that the field is the cause of the effect. Generally, several experiments are required to establish causal relations, and it is proper to be more cautious of data that merely shows a correlation to the field exposure. For example, there may be a situation in which corona-generated ozone is actually the cause of an effect, but since the electric field strength also correlates to ozone production, the biological effects actually due to ozone would also appear correlated to the field. To settle the issue in this hypothetical case it would be necessary to do further studies with only field and only ozone present.

STUDIES with HUMAN SUBJECTS

1. Sources of Information

The principal sources of information about effects on man are surveys and clinical studies of utility substation and high voltage line maintenance workers, a few laboratory studies with short exposure durations, several epidemiological studies that appear related to exposure to extremely weak magnetic fields, and a survey of persons living near to transmission lines. To date, the study of inhabitants of areas near high voltage lines has been of limited scope, and the data are of limited value. Such studies require careful design, are expensive and necessitate observations of a sufficiently large population over a long period of time. Studies of utility workers are of interest, although exposure to the HVTL fields differs with respect to intensity and duration. Several small studies exist, but none has the statistical power nor covers a time span that could answer all reasonable questions about chronic effects.

Nor would such a study be easy. A study of the feasibility of an epidemiologic study among utility workers found that there were serious problems in quantification of past exposure to strong electric fields and in determination of past exposures to chemicals (Utidjian, 1979). It was concluded that it would be possible to perform a study that could indicate any unusual patterns of mortality. At the same time the study would identify a population in which future studies could be made to investigate effects with long latencies. The recommended "historical perspective" study design would need to include several thousand workers, but excluding linemen whose exposure to strong electric fields is sporadic, and therefore not as likely to indicate electric field health effects as in the case of transformer substation workers. In addition a cross-sectional study involving extensive health examinations of about 100 exposed and 100 control persons was suggested. The difficulties of obtaining suitable dosimetric information and obtaining adequate records (due to bureaucratic difficulties pertaining to corporate health records of individuals) have so far prevented efforts to begin an epidemiologic study within the power industry (Kavet, personal communication, 1982).

Although, there is no substitute for good epidemiological data for evaluation of public and occupational health aspects of ELF exposure, at present no reliable data exist either for the utility workers, or the general population.

The controversial results of the existing "epidemiologic" studies are discussed below and are of restricted significance. Other studies, based on examination of volunteers under laboratory conditions yield data that are of limited significance for evaluation of chronic exposures.

2. Health Surveys of Utility Workers

The data on actual exposure to workers who have participated in health surveys are usually seriously limited, and until recently, little accurate information about the typical duration of exposure at or above a certain electric field strength was available. The number of exposed persons, even within the entire United States power industry is quite small (5000 high voltage linemen and perhaps 2500 switchyard workers, according to Utidjian, 1979). For this reason, diseases with low rates of incidence may not be detected. Because the portion of worklife spent at an occupation involving strong fields is limited, diseases with long latencies may be difficult to detect epidemiologically.

Because of problems with exposure and instances of inadequate documentation in some reports there is no firm basis for judgment from the human studies. As a group they provide a limited basis that shows no health effects among workers exposed in an occupational setting, with the prominent exception of a broad spectrum of problems reported among switchyard workers in the USSR and Spain and specific reproductive problems among Swedish switchyard workers.

USSR Substation Workers - The Soviet experience with substation workers in a switchyard provided the first reports of a possible electric field-related effect on human health. The conclusions of the Soviet physicians emphasized evidence for a generalized alteration in central nervous system function, especially in the autonomic nervous system (Asanova and Rakov, 1966; Korobkova and Rakov, 1968). The workers were exposed to strong 50 Hz electric fields in a 500 kV substation where electric fields were in the range 8 to 14 kV/m although most areas had fields of less than 10kV/m.

A clinical study of 45 employees was prompted by complaints from the employees after the first several months of substation operation at the new (higher) voltage of 500 kV (Korobkova et al., 1972). Thirty-seven workers complained of headache, sluggishness, fatigue and sleepiness; disruptions of the digestive system and cardiovascular system were mentioned, and one-third of the men between 30 and 40 years of age complained that "sexual weakness" had developed after 8 to 10 months of work in electric fields.

The medical examinations of the 45 employees produced diagnoses of neuropathology in 28 cases. Pulse instability (17 cases), labile arterial blood pressure (11 cases), excessive perspiration and fine tremors of the hand were diagnosed in 26 persons and attributed to a "functional disruption of the central nervous system." In four of the workers there was more serious pathology of the vasomotor control system and disorders in the secretory system were diagnosed. In four cases the neurasthenic syndrome was observed. Electrocardiographic data showed sinus bradycardia in 14 cases and evidence for slowed atrial and ventricular conduction in 10 cases in addition to observations of "diffuse changes in the myocardium". Shifts were seen in the red and white blood cell counts, and in sedimentation rate. Hypotonia (reduced systolic blood pressure) and signs of sinus arrhythmia and/or tachycardia were noted. Digestive tract disturbances were also reported.

Thus, of a group of 45 substation workers, 39 of them under age 40, 37 complained of ill health and 28 were diagnosed to have neuropathology, suggesting that a strong electric field or its collateral effects (principally, spark discharges), acting over a period of months, may lead to pathologic conditions. However, it is not possible to conclude that the reported physiologic disturbances are attributable to the electric field, because the research reports suffer a number of serious deficiencies. Of these, incomplete presentation of the data, lack of a control group and the difficulty in interpreting the manifold clinical symptoms are most serious obstacles to acceptance of the authors' conclusions.

Because effects occurred only among workers in 400 kV and 500 kV substations, it was concluded that exposures occurring in 220 kV substations did not lead to noticeable health effects.

In addition to the clinical data, Sazonova (1967) reported on physiological tests performed on substation workers. In these tests the substation workers were divided into two groups according to the type of work assignment and thus the extent of electric field exposure. The group exposed to higher electric fields had a significantly lower blood pressure, greater neuromuscular irritability and increased latent reaction time and higher error rates in a stimulus-response test. Unfortunately, the information about exposure conditions for these workers is inadequate to determine electric field strength or exposure duration and their relation to changes in physiologic function. This report also suffers from inadequate presentation of the data.

The experiences of the USSR switchyard workers may be summarized as the widespread occurence of subjective complaints that the authors' attribute to unfavorable changes in the central nervous system (Korobkova et al., 1972).

Work Rules in the USSR - Work rules to limit exposure time at field strengths above 5 kV/m and concomitant rules to eliminate spark discharges were put into effect in the USSR, and thereafter no additional evidence for a field-related health problem has been reported as complaints and "undesirable cases" have disappeared (Bourgsdorf, 1975).

Spanish Substation Workers - In Spain, Fole (1972) reported similar health effects among 400 kV substation workers. Nine subjects studied suffered headaches, dizziness, fatigue and nausea after they had begun work. These data are also indadequately presented and do not allow firm conclusions. The intercomparisons of switchyard workers, HVTL workers and low voltage lineman suggests greater incidence of abnormalities among the switchyard workers as compared to the low voltage linemen.

Swedish Substation Workers - Knave and co-authors (undated) examined 53 workers of 400 kV substations employed for periods longer than 5 years, and compared the results with a group matched for age, geographical location, and duration of employment. Data for the fraction of time that the exposed group spent during work in electric fields of different strengths showed that exposure to fields above 10 kV/m was occasional and occurred most often during repair of circuit breakers. Most of the work time was spent in fields at or below 5 kV/m.

Data of subjective complaints were collected using standard questionnaires and interviews. Eight psychological tests were performed. EEG and ECG were recorded, blood pressure measured and the peripheral blood picture examined. No biochemical tests were made. The number, sex and birth date of children (in relation to the date of employment) were noted. Complaints attributable to "neurasthenia" were found equaly in 16 of the substation workers and 17 of the reference group. Tests of exposed and control groups were negative except for a few results that the authors attribute to differences in education. It should be noted that the results of the peripheral blood study are not quoted. Tests conducted after acute exposure (defined as within 14 days of exposure) were negative except for results on a battery of psychological tests in which the exposed group showed consistently better results in tests of manual dexterity, reaction time and in a test with matrices. The authors conclude that they found "no evidence for the development of persistent, chronic health effects in high voltage substation workers as a result of exposure to electric fields."

German Substation Workers - In contrast to the finding of reproductive problems in Swedish switchyard workers, Bauchinger et al. (1981) reports no effects on offspring of 32 switchyard workers and no increased chromosomal breakage. These workers were exposed at levels up to 12 kV/m (50 Hz) for up to 20 years and were matched to 22 men not exposed to electric fields.

Chromosomal Aberrations in Swedish Substation Workers - Nordstrom et al., (1981) found more chromosome and chromatid breaks among electric field exposed workers in a 400 kV switchyard. Statistically significant results were found for a test group of 20 exposed persons (segregated according to smoking habits) as compared to suitable non-exposed controls. An asymmetry in boy/girl ratio among offspring was noted, but an overall difference in members of offspring was attributed to socioeconomic factors.

There are corresponding data from 449 male high voltage workers (Nordstrom, 1981) that strongly indicate an increased rate of stillborn and deformed children among the substation or switchyard workers and continued evidence for chromosome aberrations. The deformity rate among the offspring of workers continually exposed to strong electric fields was 8% while it was 3% for the offspring of members of the control group. The average chromosomal damage rate among field-exposed workers was 2.3 per 100 cells versus 0.7 per 100 cells in the control group. Although chromosomal damage at these rates of itself is not an indication of a health hazard, it is remarkable if the substation environmental factors (strong electric fields and spark discharges) are capable of profound effects on cells, and even more remarkable if these effects in the male are expressed by the development of defective offspring. These data require considerable investigation, but stand as a warning of a possible hazard in electric fields of about 10 kV/m.

(These findings of a cellular effect may be compared to another Swedish study (Hansson, 1981) in which a cellular effect on structural elements of brain cells was seen for rabbits exposed in a switchyard, see below.)

Hansson Mild et al., (1982a & b) investigated the possible role of spark discharges in causing chromosomal aberrations by a direct effect of the currents on samples of blood. Lymphocyte chromosome aberrations were found only when using very strong fields (3 kV/cm), just below the level at which the cells would be killed. The relevance of these fields to human exposure to discharge currents is not made clear.

USA Linemen - Other investigators do not find health effects attributable to occupational exposure in HV-utility workers and HV-line maintenance crews. In 1964 a a study of ten utility line men was initiated to investigate for overall health changes related to work experience with strong electric fields while engaged in maintenance of high voltage electric transmission line. The study was carried out for nine years although job changes meant that most men no longer worked as linemen at the end of the study. Both the initial report (Kouwenhoven, et al., 1967) and the final report (Singewald et al., 1972) found no significant health effects. Regular physical examinations were conducted by a medical team led by an internist in consultation with several specialists. The only data showing abnormal values concerned sperm levels and the authors suspected probable experimental artifact since the values varied considerably from year to year. Information about exposure of the linemen is not available, there were no control groups, and detailed data from the examinations were not presented. In comparison with substation workers it can be expected that the linemen were exposed more infrequently but to much higher electric fields.

Canadian Substation and Transmission Line Workers - Stopps and co-workers (1979) conducted a study of 11 switchyard workers in Ontario substations at 500 kV and below, and 19 others working on transmission lines at similar voltages. Estimated exposure indices for a 10 year period were developed for each subject, with a clear indication that the integrated exposure (sum of field strength-time products) was much greater for the switchyard electricians than for high voltage linemen. This study featured an exceptionally complete battery of medical, behavioral, psychiatric and psychological tests. Physiological testing included EKG, blood pressure, serum chemistry, red and white blood cell counts, biochemical measurements in blood, EEG. Psychological testing included the MMPI personality inventory, WAIS tests of cognitive skills, maze skills, reaction time. The conclusion from the study was that the thirty electric field exposed workers showed no difference in health status when compared with matched controls drawn from maintenance workers of the same utility.

In a second study 56 workers at 735 kV substations in Quebec were examined (Roberge et al., 1976). A questionnaire oriented toward possible nervous system symptoms was used and a clinical examination was carried out. The subjects examined were employed for periods longer than 4.5 years. Complete biochemical evaluations of the blood plasma revealed some statistically significant findings: eosinophilia was observed ($p < 0.001$), and a number of plasma proteins and metabolites were altered, including glucose, creatinin, uric acid, calcium, total bilirubin, iron, transaminase, total protein level, alkaline phosphatase (all at $p < 0.05$). Despite these positive findings this study generally supports the evidence for no health effect related to occupational electric field exposures, especially because the reported shifts in blood cells and blood biochemistry are difficult to interpret, and were within clinical norms.

French Residents Near HVTLs - Analysis of the medical records for persons at varying distances from HVTLs disclosed little evidence for a distance-related difference in the consumption of medical or pharmaceutical services (Strumza, 1970). The "high" exposure group lived within 25 m of 200 to 400 kV transmission lines, while the "low" exposure group lived more than 120 m from the lines. The few inter group differences that were found are likely not due to the proximity of the transmission line.

3. Studies of Humans in the Laboratory

There are only limited data from human subjects exposed voluntarily to electric fields, low-level currents or spark discharges under laboratory conditions. These data are valuable because of the greater control over extraneous influences in comparison with occupational exposures and because they involve the human organism rather than animals that may differ electrically, biologically and behaviorally. Of course, studies with humans are limited to physiological and behavioral observations that cause no harm and the test sessions are relatively brief. Also, in dealing with humans, the experimenter assumes an extra burden to avoid artifacts, e.g., the experimenter must be careful not to confound the data by slight cues.

Laboratory Exposures at Freiburg, Germany - Beginning in 1974 R. Hauf and co-workers in his laboratory in Freiburg reported on a total of over 100 human subjects exposed to strong 50 Hz fields (up to 20 kV/m) during laboratory test sessions that involved relatively brief exposures to the fields. In the first report (Hauf, 1974) no field related effects were observed on reaction time, blood pressure, pulse rate, electrocardiogram, or electro-encephalogram but large, rapid changes in some red and white blood cell parameters were seen. Each of the three hour test sessions included two exposures for 45 minutes to fields at 1, 15, or 20 kV/m and the testing lasted three successive days. Detailed descriptions of the experiments and reports of the data are available in the work of G. Hauf (1974), Rupilius (1976) and R. Hauf (1976). Data of similar measurements reported by Eisemann (1975) showed no effects on human subjects exposed for periods of up to three hours to a conduction current of 200 uA. This current was applied by electrodes placed on the ankles and under the arms and was intended to simulate the displacement current of similar magnitude that flows in humans exposed to fields of 15 kV/m at 50 Hz.

Johansson, et al. (1973) reported no significant behavioral changes among 20 humans exposed to an electric field of 20 kV/m (50 Hz). The exposed subjects performed as well as controls on tests of reaction time and on psychological tests, and responses to a questionnaire disclosed no significant differences in perceived levels of discomfort between the test and control groups.

Rupilius (1976) conducted a study in man where 3 days exposure to magnetic field at 50 Hz was combined with a 20 kV/m electric field. Observation for up to 24 hours post-exposure disclosed no change in blood chemistry.

Effect of 10 Hz on Circadian Rhythms - Wever (1968 and 1974) performed several studies that indicate the influence of weak ELF electric fields on human circadian rhythmicity. In particular, a 10 V/m, 10 Hz square wave electric field appears to influence biorhythms while the complete absence of electric fields leads to desynchronization of certain biorhythms. These data are difficult to interpret in reference to HVTL electric fields, because in the normal environmental situation there are many cues (Zeitgebers) by which circadian rhythms may be synchronized. The data point to the existence of a detector of weak electric fields but do not address the issue of the possible health effects of imposed ELF fields.

Magnetic Field Effects in Man - In tests of cognitive skills among men exposed for 24 hours to a magnetic field of 1 G at 45 Hz (Gibson and Moroney, 1974) found statistically significant differences on tests of speed and accuracy in the addition of numbers, and effects were also seen on a task requiring symbol memorization. However, in one of the tests the exposed subjects showed poorer performance, while in the other their performance was improved. The results of this preliminary experiment cannot be given a great deal of emphasis in view of the authors' hesitation to make strong conclusions from slight effects with a few subjects, in view of other tests in the same study that showed no disturbance of central nervous system function, and in the absence of other data suggesting that weak magnetic fields (which induce an electric current much weaker than that induced by the HVTL electric field) are capable of such effects.

Beischer and Brehl (1973) observed a slight, statistically significant, transient elevation in triglycerides and pre-beta lipoprotein levels in the blood of subjects two days after exposure to a 1 gauss 45 Hz magnetic field for 10 or 22.5 h daily over a period of up to 7 days. No other blood chemistry changes were seen. The significance of this finding was doubted by the authors who emphasized the small number of subjects and the preliminary nature of the results.

Perception of Fields and Discharges - Deno and Zaffanella (1982) found that about 5% of the subjects perceived a field of about 1 kV/m with a median level of perception at 7 kV/m, and levels of annoyance that begin at 5 kV/m, although the median value is greater than 20 kV/m, the highest tested. Results for spark discharges varied widely for different points of body contact. Thresholds for perception of discharges were as low as 1 kV/m (median value 2.7 kV/m). Similar data were obtained by Takagi and Muto (1971) who found the human threshold for pain was at 6 kV/m in tests conducted while the subjects held an umbrella in an electric field.

Krivova et al., (1975) report that persons experiencing microshocks administered by capacitance discharge (with unspecified electrical parameters) had altered neurophysiologic functions. The changes were characterized as a disruption of the normal "bi-lateral synchronization in the brain". The changes were reversible insofar as the reported changes were evident shortly after exposure, but were not present at later examinations.

Hylten-Cavallius et al. (1975) obtained data on human perception of shocks between a point and the fingertip. Shocks were characterized as "perceptible" at a voltage of 2.6 kV, "light" at 6 kV, "acceptable" at 8.4 kV and "heavy" at 9 kV. These data do not directly estimate the shock intensity in an electric field. The authors found that total charge in the shock, rather than the voltage determines the sensation, so that, e.g., only 350 volts would be required if a massive object (6,000 pF capacitance) were charged by the electric field.

Extensive tests of human reactions to transient discharges are being conducted by Reilly and Larkin (1981). Preliminary results indicate an unexpected threshold dependence on polarity of a dc electrode, but further data are not yet reported.

Schmitt and Tucker (1973) performed a study of human perception in fields of 1.5 and 15 G at 60 Hz. Although the initial investigations showed that certain subjects did perceive these fields, further studies with better shielding from acoustic stimula showed that such magnetic fields are not perceived.

Magnetophosphenes in Moderately Strong Magnetic Fields - In man, ELF magnetic fields of moderate intensity (about 100 G or more) produce visual phenomena ("phosphenes", such as the patterns seen in total darkness or produced by gentle pressure on the eyeball) that are similar to electrically produced phosphenes (D'Arsonval, 1893; Barlow, et al. 1947; Seidel, 1968; Oster, 1970). Using human subjects Lovsund et al., (1980) have determined the frequency and magnetic field strength parameters for phosphene stimulation, and using in vitro studies found an electrophysiological response in frog retinal ganglion cells that shares properties with the human data. Apparently, the magnetic phosphene is related to the induction of electric currents in the retina, although a detailed model is not available. These data establish one example in which electrically excitable tissue (retina) responds to very weak electric currents, although their magnitude is uncertain. The observed frequency dependence of the effect (peak effects at about 30 Hz) may indicate properties of the transduction or, with perhaps greater likelihood, properties of the visual system of the brain.

Cancers in Humans Exposed to AC Fields - Several recent epidemiologic reports present contradictory evidence for an increase in the incidence of cancer among various groups. In some studes there appears to be an association of cancer with greater exposure to very weak magnetic fields that are of a magnitude commonly found in the environment, while other studies provide preliminary evidence for a correleation of cancer with jobs that may involve exposure to strong electric or magnetic fields.

Wertheimer and Leeper (1979) reported a two to three-fold greater rate of leukemia for Colorado children whose homes were located in regions that presumably had higher 60 Hz magnetic fields. Classification of houses according to the current capacity of the low voltage secondary wires was used as an approximation for the 60 Hz magnetic field strength which was estimated at a median value of 7 milligauss (0.7 uT) for the highest fields and about 1 mG (0.1 uT) for the lowest fields. These magnetic field strengths may be compared to fields of about 10 to 300 mG in the vicinity of HVTLs. A later study (Wertheimer and Leeper, 1982) extended the analysis to include adult cancers for which statistically significant, but weaker associations were found. Each of these studies has limitations common to epidemiology: (1) The techniques used for scoring a residence within the range from "high" to "low" current may introduce errors. (2) There is the usual difficulty in assuring that the study populations are truly comparable with respect to occupational, social and economic factors, and not contaminated by extraneous factors known to cause cancer, such as chemical pollutants, or possibly the levels of traffic.

In light of these well known problems, the authors seem to establish that the study was soundly conceived and based on adequately controlled data. Several internal consistencies of the data, are cited as evidence in favor of the hypothetical link between cancer and magnetic fields. These include observation of preferred incidence of childhood leukemia in males, a greater cancer incidence near substations where current flows are greater, a reduction in the apparent potency of the magnetic field as a cancer agent for persons past mid-life (55+ years), at which time other causes of cancer would dominate, and appearance of a latent period following initial exposure to the stronger magnetic fields. Less supportive were the findings that only trends were seen for excess leukemias among first born children or among the offspring of older mothers, although both effects are expected. The data for adult cancers show a dose-relationship and the magnetic field association was most readily seen in cases where confounding exposure to carcinogens was likely to be absent.

The authors suggest the possible role of the magnetic fields as promoters or co-agents of the cancer process, rather than as a solitary cause. They emphasize that the significance of their data would be in the ubiquity of situations with continual weak magnetic fields, rather than the slight individual health risk represented by a doubling in a cancer with a low rate of incidence. These findings have support from a recent Swedish study that is, at present known from a news report (Microwave News, 1982). Tomenius and co-workers are reported to have found greater cancer rates in children whose homes had ambient fields of more than 3 mG. They also are reported to have found a higher tumor rate among children living near (undefined) 200 kV power lines.

Fulton et al. (1980) replicated the central portions of the Wertheimer and Leeper study for childhood leukemia using a study population in Rhode Island, but found no link between cancer and the magnetic field. Their techniques were generally similar to those used in Colorado, although the significance of the technical differences is unknown.

In a letter to the editor, Milham (1982) shows a table derived from an extensive data base on proportional mortality rates in Washington State that indicates greater incidence of leukemia for job classifications that are superficially related to electric or magnetic field exposure. Based upon data from Los Angeles, Wright et al., (1982) also report increased leukemia among men who are presumably occupationally exposed to electric and magnetic fields.

The data that relate cancers to weak fields are not supported by any quantitative physical theory that could affect cellular processes in order to induce or promote cancerous transformation.

The impact of these data on the HVTL issue is difficult to assess. On the one hand, the HVTL magnetic fields are much stronger (up to 300 mG) and if a linear dose response relation were established, a significant rate of cancer promotion might occur. Studies of a limited number of utility workers (see above) have disclosed no pattern of cancer. If magnetic fields of the order of 10 to 300 milligauss (similar to HVTL near fields at points near ground) were established as significant promoters of cancer, there would be need for protective action. In comparison to the potentially widespread problem associated with other environmental sources of magnetic fields in the range above about 5 mG (household appliances, many industrial machines), the transmission line contribution would be minor, i.e., isolated and well localized.

The association of very weak magnetic fields with cancer, especially in children, will certainly result in further controversy, further evaluation of the epidemiologic techniques, and further laboratory research. These 5 mG fields are very much weaker than most magnetic fields studied, and the induced electric fields are also much weaker than any studied experimentally, excepting the case of certain electro-sensitive fish. The reader will already appreciate that, at the electric or magnetic field levels produced near HVTLs, there is little agreement that a reasonable, physical mechanism could exist. But at the much weaker levels of about 5 mG (60 Hz) there is almost no foundation of theoretical or experimental data that would support the epidemiologic findings. For this reason alone, there should be considerable study before the implication of these epidemiologic studies is accepted as guidance for future research aimed at establishing a causal link between cancers and very weak 60/50 Hz fields.

Human Exposure to Very Low Level Fields - Employees exposed to very low level electric fields (generally less than 0.05 volts per meter and accompanying magnetic fields of 0.1 gauss) at the site of a test communications antenna (Project Sanguine/Seafarer) were examined for evidence of pathological changes related to field exposure. An investigation for neurological or other symptoms found no field-related effects (Krumpe and Tockman, 1972, 1974). Studies such as this one do not stand opposed to the foregoing epidemiological data on cancer rates, because of the small size of the study populations and duration of exposures and duration of the study period.

SUMMARY of DATA from HUMAN EXPOSURES

The data from humans exposed to electric fields are not an adequate basis for decision on either the acute or chronic effects of exposure to electric fields of 1 to 10 kV/m. The data from the USSR, Spain and Sweden give some evidence for pathologic effects that can be attributed to exposure in the substation environment which includes strong electric fields. However, the pathologic changes seen in the initial studies in the USSR are not clear evidence for an effect of the electric field itself. From further Soviet statements (Bourgsdorf, 1975), and in view of the explicit recognition that spark discharges should be eliminated, there is reason to believe that the experience of the 500 kV substation workers was related to the repeated incidence of spark discharges, perhaps to the exclusion of any direct effect of the field. Other suggestions of an effect due to occupational exposure to strong fields are the asymmetry in boy/girl ratios among the offspring of Swedish electrical workers, increased rates of abnormal or stillborn offspring and evidence for chromosomal abnormalities in peripheral cells of these workers. The appearance that Swedish switchyard workers are subject to genetic problems does not find support from a study in Germany or from studies of linemen in the USA.

The epidemiologic evidence for an increase in the incidence of certain malignant diseases among persons putatively exposed to electric or magnetic fields at 60 Hz can not been fully evaluated (Wertheimer and Leeper, 1979; Wertheimer and Leeper, 1982; Fulton et al., 1979; Milham, 1982; Easterly, 1981; Wright et al., 1982). The electric or magnetic field strengths involved in these studies are very much less than the HVTL field strengths. If these data prove to be reliable indications of an effect of the fields, the problem is far broader than the fields of transmission lines. Remedial measures that might then be required would probably have a greater impact on many other situations where electric and magnetic fields are produced, as contrasted with the HVTLs. Apart from the need to interpret epidemiological data cautiously because they can only indicate statistical relations but not causal relations, these data are difficult to interpret because the presumed magnetic field intensities are so very weak that plausible physical mechanisms for interaction have not been suggested.

In summary, health surveys of persons exposed occupationaly indicate no confirmed health hazard to workers associated with 50/60 Hz electric (and magnetic) field exposure. Exceptions may exist with respect to observed genetic effects in the strong fields of a substation. Laboratory data suggest that only mild, reversible physiological changes may occur, but these are not established. The epidemiologic data of persons exposed occupationally or in the home point to a small, but not ignorable, increase in the rate of certain cancers among persons exposed to low level 60 Hz magnetic fields, and possibly an increased rate of birth defects and stillbirths for the offspring fathered by males exposed to strong fields of a substation.

CRITICAL OVERVIEW of the BATTELLE ELECTRIC FIELD STUDIES

A large and diverse research study on the biological effects of 60 Hz electric fields is ongoing at the Battelle PNW Laboratory in Richland, WA. This research program deserves special summary because of the broad scope of the research, the relevance of many of the results to the discussion of health effects, and because it is generally recognized that the work has been characterized by a high degree of technical competence. In particular, the exposure conditions are well thought out and executed, bioassays have been thoughtfully chosen, many of the individual studies demonstrate scientific sophistication in the choice of hypotheses and the tests used to examine them, the animal handling and biological analyses yield biological data of satisfactorily low variability, and statistically appropriate sample sizes and analysis techniques have been employed. In order to achieve reliable conclusions from the data, particularly where small effects were seen, there has been replication of many experiments. These factors are of note because of prior experiments (involving the first efforts at exposure of animals to strong electric fields) that were inconclusive because of technical problems which the Battelle studies took care to avoid.

Of these problems, the issue of spark discharges received by the animals from the watering system has been a topic of special note. Presumably data from experiments in which animals are continually subjected to above threshold discharges to the mouth or tongue may reflect the effect of these discharges rather than the direct effect of electric fields. Attempts to quantify the electrical situation that would clarify the problem have shown that because the rat impedance to ground varies over a wide range no single value for voltage differences, current flow or shock energy can be used to estimate the magnitude of the electrical problem (Kaune et al., 1982). However, attempts to estimate the biological potentcy of the shocks, while incomplete, indicate that the animals are easily able to adapt to the influence of the shock discharges (Kaune et al., 1982). Thus, the importance of shock discharges in fields up to

100 kV/m is still uncertain, and their role in contaminating research results unclear. It is reasonably certain that studies such as those at the Battelle laboratories, in which the potential difference between the rat and the watering system is about 1 volt (Free et al., 1981) do not subject the animals to shock currents or discharges of significance.

The initial phases of the project involved extensive screening studies that appear to have been selected for several reasons: (1) to replicate previous experimental research (2) to examine the physiological and behavioral factors that are well established indicators of health effects by environmental agents in general; and (3) to examine for factors that might be specific to an electric field interaction with the nervous system. Following the screening studies the research has been directed toward understanding the mechanisms for the biological effects uncovered by the prior research.

The studies are conducted in small laboratory animals (rats, mice and guinea pigs) and in a specially bred pig, the Hanford Miniature Swine. An excellent analysis of the electric field and current density patterns for each of these species, and a comparison with man are an integral part of the project, and essential to interpretation of the laboratory data.

Overall, techniques that would disclose effects on basic physiologic parameters such as growth and development, morbidity, blood cell populations, serum chemistry, cardiovascular function, neurophysiologic status showed consistently negative results for either biological effects or evidence of a health deficit among the animals. The preponderance of negative findings (to be reviewed briefly below) emphasizes that the electric fields tested did not affect survival of the organism, or introduce any physiologic changes indicative of a health hazard. Comparisons of the electric field influence with toxic chemicals, radiation, etc. are not meaningful.

A few biologically interesting data show clear electric field effects. These data represent a small fraction of all the studies, but are of great interest because the data touch on areas in which other laboratories have found effects and because they reinforce the suggestion that the electric field influence is quite unlike that of other environmental agents.

Positive findings in the small animal studies occurred in several behavioral tests, in neurophysiologic tests involving synaptic function, in a study of biochemical levels in the rat pineal gland, in tests of the rate of bone fracture repair, and a few other areas. Other data (sometimes linked to the significant effects by reasonable hypothesis) showed inconclusive evidence for field effects either by trends in the data or by large variability in the data.

The multi-generational study of swine has produced startling, but inconclusive evidence for teratologic effects. Because the effects seen in the subsequent breedings are contradictory and because they are not so far reported in studies of rodents, it is difficult to interpret the data. On the other hand, the degree of fetal malformations and frequency of occurrence are striking and, while inconclusive, cannot be ignored in a discussion of electric field effects. It will be seen that while the data are not convincing evidence for an effect of the electric field, there is no satisfactory way in which to "explain away" the results so that the electric field is not implicated. Because of the cost and lengthy time for such studies, replication of the study is not now planned, but other animal models will be used to investigate for teratologic effects (Phillips, 1982).

The conditions under which the Battelle studies are conducted (generally 100 kV/m rms, 60 Hz unperturbed vertical electric field, grounded subjects) are in many ways comparable to exposure of a human being in a strong transmission line electric field (in the range of 1-10 kV/m). However, scaling from quadrapeds to man cannot be exact, and until a mechanism for interaction is known, the correct scaling from laboratory animals to man is impossible. Mutual shielding of animals in a cage results in an effective time-averaged field estimated at 65 kV/m for the unperturbed 100 kV/m fields (Kaune, 1981). Shape-dependent concentration of the field results in a maximum surface field at a rodent's back that is enhanced about 3.7

times over the incident field, or in terms of the effective field of 65 kV/m, the effective surface field would be about 240 kV/m (Kaune and Phillips, 1980). The distribution of current within the rodent body results in current densities that are generally below those in a human exposed to a 10 kV/m field, but generally in excess of the current densities in man for a 1 kV/m field.

The swine study used an unperturbed electric field of 30 kV/m which results in a maximum surface field of about 200 kV/m (Kaune and Phillips, 1980) and in internal current densities that, as for the rat, fall in the general range of current densities in man for exposures above 1 kV/m, but below10 kV/m, with significant variations for different sites within the body.

After completion of some of the studies, it was discovered that due to an improperly repaired transformer, exposure levels in some of the experiments were drastically reduced from those that had been previously reported (Phillips, 1982). The affected experiments seem to be those that involved long-term exposures of mice for immunological tests, infectivity study of chickens, part of the work with rat melatonin levels and certain behavioral tests. As a result some studies (mouse immunology and cytogenetics), for which negative results were found, will be repeated. A highly interesting consequence of the reduced exposures is that there are now limited data to suggest some electric field effects are expressed to about the same degree in weak as in strong fields. In particular this seems to be the case for rat pineal gland melatonin levels in an electric field of 1.8 kV/m (Anderson, 1982). A similar conclusion may be inferred from rat behavior tested at 1.8 kV/m (Lovely, 1982).

These data contain the hint that some electric field effects may exist over a very broad range in electric field strength which extends to the level of electric fields in the home or workplace.

1. Negative Findings at Battelle for Most Physiologic Parameters

The vast majority of tests of physiologic parameters showed no effect in studies conducted with rats in electric fields of 100 kV/m (unperturbed), (effectively equivalent to 65 kV/m for multiply caged animals.)

In some cases these data contradict earlier research in other laboratories that may have been flawed by procedural problems, and where important this fact is noted below.

Cardiovascular Function - Rats exposed for periods of 1 to 4 months showed no field-related changes in EKG, heart rate, blood pressure or vascular response. In parallel to these negative effects of prolonged exposure, no effects were found during 1 hour exposures (Hilton and Phillips, 1980). Response to cold stress after a 1 month electric field exposure was unaltered, and associated indicators of stress response (plasma levels of corticosterone and thyrotropin) were not different in the exposed animals. These data are in contrast to the findings of Marino (1976) who reported changes in blood proteins and corticosterone that were interpreted as evidence of chronic stress. Previously reported effects on the EKG (Blanchi et al., 1973b) were not found.

Metabolic status, organ weights, growth - None of these parameters was affected by field exposures of 1 to 4 months. Previously reported effects (Marino et al., 1974a,b,c) on growth, water consumption and glandular weights were not observed.

Immunology - Tests of the serum levels of the important immune system proteins, or of the primary antibody response to keyhole limpet hemocyanin (KLH) showed no field-related effects. Cell-mediated immune response gave negative results in tests of the mitogen-stimulated response of spleen cells from mice exposed for 1 to 5 months. Both these studies appear to have been in a very much reduced electric field strength of about 0.120 to 0.250 kV/m, in contrast to what was believed at the time of the original reports (Morris and Ragan, 1979; Morris and Phillips, 1981). The immunologic response of chickens to leukemia virus was unaffected by exposure to an electric field of about 1.8 kV/m (Schneider and Kaune, 1981). These two studies, flawed by the inadvertently low level of electric field, may be repeated.

Blood Cell Counts and Serum Chemistry - Very complete studies of blood cell populations and serum chemistry were completed and replicated in female rats and mice exposed for 15, 30, 60 or 120 days (Ragun et al, 1981). In contrast to several other studies (e.g., Blanchi et al, 1973a; Hauf, 1976; Asanova and Rakov, 1966; Dumanskiy et al., 1975; Marino et al., 1976b,c; Poznaniak et al., 1979; Meda et al., 1972) no consistent effects were observed. The prior studies, conducted at various field strengths from 100 V/m to 150 kV/m (50 and 60 Hz) showed results such as increased concentrations of neutrophils and eosinophils, lowered numbers of lymphocytes, changes in various serum constituents (SGOT, LDH, glucose, calcium, BUN) and alterations in concentrations of serum proteins. The Battelle rat studies indicated no effects on counts of erythrocytes, reticulocytes, leukocytes, lymphocytes, neutrophils, platelets, or bone marrow cells that were repeated in both the original and replicate studies. Some small differences of strong statistical significance were observed in a number of the cell counts, with the suggestion (this reviewer's observation) of a clustering of effects in the replicate study at the longer exposure times. The authors' interpretation is that no consistent effects were found and that the occurrence of a number of statistically significant results (among hundreds of "t-tests") "emphasizes the need for replicate designs and appropriate statistical analyses." This reviewer agrees that these studies indicate no changes of physiological importance, but in the absence of more refined statistical analysis than that used in the study, it is uncertain if the electric field exposure was entirely without effect.

The data for serum chemistry were similar, and indicate no large or important physiologic changes. Those few observations of a statistically significant change are of doubtful relation to electric field exposure. The hematology and serum chemistry tests for the 120 day exposure in mice apparently were conducted at very reduced electric field strengths of 0.120 to 0.250 V/m.

Endocrine system - The possible influence of the electric field on the rat endocrine system was assayed by measurements of plasma levels of several hormones (LH, FSH, TSH, growth, thyroxin and testosterone), measurement of body and organ weights. Although some statistically significant results occurred, these were not consistent (Free et al., 1981).

An exception is the finding of a change (30-40% reduction) in serum testosterone at a significant level in one study and as a trend in the replicate study. (See below.)

Neurophysiology - Tests of synaptic function were performed in rat sympathetic cervical ganglia excised from animals exposed for 30 days in comparison with tissues from unexposed rats. The postsynaptic compound action potential was unaffected in size or time course, conduction velocity was unchanged and fatigue of response was unaltered. A clearly significant effect was seen on a test of neuronal excitability (the "C-T response" or "conditioning-test ratio response") and is discussed below. Other tests on sciatic nerve (chosen as an example of myelinated nerve) and vagus nerve (unmyelinated) were negative for evidence of a field effect. Most tests of neuromuscular function were negative, but a slight effect on fatigue recovery in slow twitch muscles was observed (see below).

Three day old miniature swine exposed in utero to 60 Hz electric fields of 30 kV/m showed no field-related changes in their performance on two tests of neuromuscular developement. In the first test the animals were placed on their backs and observed for speed with which they righted themselves. In the second, they were timed as they walked an inclined plane (Lovely et al., 1982).

Multi-Generational Study in Mice - A study of four generations of mice conceived, developed, born and raised in a weak electric field of 120-250 V/m showed no clear effects except possibly in the data on tooth eruption among males (Smith, Buschbom and Sikov, 1981).

Histopathology in Mice - Entirely negative findings were obtained for differences between exposed and sham exposed animals upon histopathologic examination of bladder, prostate, bowel, thyroid, lung, heart, brain, trachea, vagina, uterus, kidney and liver (Renne, 1979). It is not clear, but it appears this mouse study was also conducted at 0.120 to 0.250 kV/m, a field strength very much reduced from the intended 100 kV/m.

Behavior - After preliminary studies that showed rats responded to the presence of the electric field (Hjersen et al., 1980), the conditioned taste aversion paradigm was employed to determine if the electric field was distasteful to the rat (Creim et al., 1981). Rats were given saccharin sweetened water just before exposure to the electric field. If the field experience were aversive, they would be expected to avoid the saccharin water in the future. No differences between the behavior of exposed and sham exposed animals were observed in this test at any field strengths of 32, 65 or 130 kV/m. In a subsequent variation, both test and control animals were made ill with a toxic agent to which they demonstrated aversion, but there was no increment in aversion due to field exposure.

2. Positive Results in Battelle Behavioral Studies

Behavioral tests at Battelle, as elsewhere, have given clear indications that rat behavior is affected by the presence of the field. The data are surprisingly rich in that responses change in nature with field strength, time of day, and the order in which fields of different strength are presented. There have been speculations that the rat responses are "trivial" because they are merely the result of a sensory phenomenon as the result of electro-mechanical vibration of body hair or vibrissae. Attempts at Battelle and elsewhere to demonstrate this hypothesis have not been conclusive (Phillips and Kaune, 1977, Stern and Laties, 1981, Stern and Laties, 1982). Jaffe (1982) has demonstrated the existence of mechanoreceptors in the cat paw that also reponded to strong electric fields. At present the hypothesis is neither well supported or disproven.

The initial behavioral data of Hjersen et al. (1980) demonstrated that rats preferred the shielded side of a shuttlebox when the other side had an electric field of 90 kV/m (for 45 minutes at 60 Hz). In tests lasting 24 hours, the rats showed a preference for the shielded side at field strengths above 75 kV/m but preferred the field at 50 kV/m or below. However, this field preference was observed only during the light period (inactive phase) of the daily cycle. Evidence for an immediate recognition of the field condition was found in the increase of traverses in the box shortly after the field is applied. Hjersen et al. (1982) report similar evidence for a preference for the shielded region among Hanford Miniature Swine exposed during a 24 hour test at 30 kV/m.

Groups of 30 rats repeatedly exposed to fields of 25, 50, 75 and 100 kV/m during 50 minute tests, showed differential field response depending upon whether the fields were presented in ascending order (no aversive response in the shuttlebox test), or random or descending order (positive aversive response at 75 kV/m and 100 kV/m, as observed in previous tests).

Another recent study (Lovely, 1982) indicates further complexity in rat responses in strong electric fields. In this study rats exposed to the field (100 kV/m) switched from their prior preference for saccharin-sweetened food if obtaining the food required entry into the electric field exposed side of the shuttlebox. Viewed together with the same experimenter's failure to find a taste aversion response (see above), it will be seen that the study of rat behavior in electric fields promises to yield interesting behavioral data for which a mechanistic understanding is required.

3. Positive Findings in Battelle Physiology Studies

Neurophysiology - The neurophysiologic studies have provided two tests in which clear, replicable effects were seen. In the first (Jaffe et al., 1980) neuronal excitability was elevated in rat superior cervical ganglia freshly removed from the animal after a 30 day exposure at 100 kV/m (65 kV/m effectively). This effect was evident from results of the "conditioning-test response ratio" (C-T ratio) studies in which the the presynaptic fibers were stimulated with above threshold stimuli. The height ratio of a pair of action potentials was observed as a function of the interval between the pair of stimulating pulses with clear evidence (replicated) that the exposed animals showed greater amplitude of response for a wide variation in the inter-pulse intervals. Other parameters of the performance of this same nerve tissue were tested and found unaffected by the field exposure. These included the amplitude of the compound action potential (elicited by a single pulse), its rate of rise and fall, conduction velocity in the nerve, frequency response, post-tetanic response, and response after prolonged high frequency (20 Hz) induced fatigue.

These data are of special interest for several reasons. (1) The data are especially clear-cut. (2) There is widespread interest (based upon other research and argument from the electrically sensitive nature of the nervous system) in the possibility that nervous tissue is particularly sensitive to electric fields. (3) The data are of a type that invite mechanistic investigation. (4) Because there is no classically recognized mechanism whereby the weak currents that flow during electric field exposure of the rat could alter properties of tissue, it is especially challenging that an effect is observed. (5) The effect demonstrates a functional change that persists for at least several tens of minutes following the end of the exposure and dissection of the tissue. (6) The results are consistent with other experiments that find no apparent neuropathology or gross functional deficits. The observed neurophysiologic field effects are not of such magnitude that a pathologic condition should be easily observed.

Neuromuscular Function - Jaffe et al. (1981) reported that rats exposed for 30 days to a 100 kV/m electric field showed an effect on recovery from fatigue in one class of muscle, the slow-twitch soleus muscle. However, in other tests of the same neuromuscular apparatus, and in all tests involving a fast twitch muscle of the same animals, no significant effects were found (although a trend is evident in one replication of the study of fast twitch muscle). The interpretation of the various tests led the authors to the conclusion that neither nerve or muscle functions were directly affected and that the apparent cause was neither in neural or muscular cells, but could be due to a reduction in blood flow to the muscle. Evidence to support this suggestion has not been developed, and the observed effect on neuromuscular response remains of interest, especially because of the possibility that the mechanism may involve fundamental biochemical processes at the cellular level.

Bone Fracture Repair - This study by McClanahan and Phillips (1981) follows a report of similar effects by Marino et al. (1979), in which significantly weaker electric fields were used. In the Battelle study the repair of surgically fractured bone was retarded in the animals exposed to a field of 100 kV/m (14 days). Eventually, the exposed and sham exposed animals achieved identical degrees of bone repair. In related bone studies, no effects were observed in the rate of bone growth in immature rats. Bone healing during exposure to various dc, ac electric currents and fields and to pulsed magnetic fields has been the focus of considerable research interest (e.g., Watson, 1979, for review). The authors of the Battelle study suggest that the current density in the leg during field exposure was about 1.4 uA/cm^2. Although a direct field effect on the fracture repair process may be inferred, the authors suggest it is possible that these results are due to a field-related increase in muscular activity that may have interfered with the rate of fracture repair, without affecting the eventual completion of successful bone union.

Rat Pineal Melatonin and SNAT levels - Anderson (1982) and Wilson et al. (1981) report on significant decreases in the nocturnal concentrations of the pineal gland neuroendocrine substances melatonin and SNAT (serotonin N-acetyl transferase) after exposure at 65 kV/m (39 kV/m effectively) for

30 days. Tests at intervals of from 1 hour to 3 weeks after the start of exposure indicate that the effect requires three weeks to reach a significant level (Anderson, 1982). It is of special interest that the response is strongly coupled to the rat circadian rhythm, and in the rat that rhythm is strongly influenced by the pineal gland. The most recent studies indicate an opposite effect on the serotonin metabolite melatonin (depressed at 0200 h, during the rat active phase, in the exposed animals) and SNAT (also depressed), as compared with the alternative serotonin metabolite, 5-methoxy-tryptophol (elevated at the same time of day). Since these alternative metabolites both arise from serotonin it appears that the biochemical pathway has been switched in the field exposed animals.

Wilson et al. (1981) speculate that the effects on the pineal gland may be mediated by increased excitability of nervous system components that are afferent to the pineal, especially in the absence of evidence for a humoral factor that might regulate serotonin metabolism in the pineal gland. Because the tissue level current is so low, possible mechanisms must consider transduction at the cell membrane.

In light of other recent findings of electric field effects on circadian rhythmicity (Russell and Ehret, 1982) these data are very interesting, and taken together with recent behavioral data (Hjersen et al., 1980; Hjersen et al., 1982; Lovely, 1982b) that also show a dependence on the circadian cycle, these data may indicate a significant effect on the biochemical status of the exposed rat. It is reasonable to expect that other parameters that exhibit a circadian rhythm may require testing at various times of the day. It is possible that more sensitive indices of field influence would be found if experimental observations were timed to coincide with the active phase of the rat cycle (at 0200 h, dark phase) where the maximal effects are seen here.

The peculiar nature of the electric field interaction in the rat is made striking by the fact that in addition to the data collected following exposures at 65 kV/m, some studies on rat pineal function that produced positive results were conducted in a weak electric field of only 1.8 kV/m (Anderson, 1982; Phillips, 1982).

Endocrine response in Rats - Male rats exposed to 65 kV/m (39 kV/m effectively) for periods of 35 and 120 days showed reliable, statistically significant decreases of 30-40% in the plasma levels of testosterone, and changes in corticosterone after 120 days exposure (Free et al., 1981). The reduced testosterone is possibly due to the effect of a small current that flows through the testes when the rat's scrotum is in contact with the ground plane.

Other endocrine factors (luteinizing hormone [LH], follicle stimulating hormone [FSH] and prolactin) were not significantly influenced, but an interesting observation is a shift in the oscillatory pattern in FSH and corticosterone levels that may be evidence of a field-related phase shift in hormone production.

Multi-Generation Study in Hanford Miniature Swine - A major project to expose three generations of swine in a 30 kV/m electric field (20 h/day) has been completed with evidence for strong expression of teratologic effects that cannot be convincingly attributed to the field exposure, nor can the influence of the field be discounted. In order to understand the internal contradictions of the data that result in this unsatisfactory situation, it is necessary to understand the experimental design.

Beginning in June, 1978, 48 eighteen month old females of a specially bred swine (Hanford Miniature Swine) began the study. These sows are the "F_0" generation. After four months of exposure these animals were bred with boars who were not exposed to the field. The female progeny (F_1) were bred after 18 months of continual exposure, and subsequently their progeny (F_2) were produced. In addition some of the F_0 sows were bred a second time, while others were sacrificed for study.

Various biological studies were performed on animals from each of the generations in order to assess growth and development, reproductive success, teratology, hematology and serum chemistry, immunology, cytogenetics, neurophysiology, pathology and behavior. A published report of the results is not yet available, but information from interim reports (Phillips et al., 1979) and presentations at meetings (Kavet, 1982; Kavet, 1981)) provide information on the research protocol and the findings to date. (Due to the complexity of the data obtained, some marginal "effects" of little apparent significance are omitted in this brief summary.)

No effects have been observed in the areas of hematology, serum chemistry, immunology, neurophysiology and mortality in the F_0 sows, and a slight difference in body weight appears unimportant. It was observed that the pigs preferred the field-free area at night (similar to the rat behavior findings).

It is clear that continual exposure had no effect on the health of the sows.

The teratologic results found at the first breeding showed fewer stillbirths, fewer mummified fetuses among the exposed pigs, and lower rates of infant mortality. Of these effects, the differences in embryonic deaths (0 vs 7), fetal deaths (0 vs 8) total malformations (2 vs 6) or numbers of litters affected by minor malformations (2 vs 4 out of a total of 7 litters) all show a consistent incidence in teratology among the unexposed animals. In the absence of teratology rates for this breed, it is not possible to venture the hypothesis that the electric field somehow inhibited teratologic changes. Neonatal mortality among the F_1 progeny showed an 11% rate of stillborn among the unexposed, and just 4% among the exposed group. Finally, the exposed male progeny had significantly lower body weights (381 g vs 425 g).

However, a very different pattern of teratologic effects was found upon the second breeding of the same sows, who by that time had been field-exposed for 18 months. The progeny of this breeding were examined while *in utero*. There were greater teratologic effects in the *exposed* group, including numbers of runts (7 vs 1), of which 4 of the exposed runts were malformed and the 1 non-exposed runt was also malformed. In all, 6 of 16 exposed litters showed major malformations whereas none of the 7 unexposed litters had major malformed fetuses.

Behavioral and neurophysiologic tests disclosed a pattern of differences in function that was not consistent in showing either a deficit or benefit among the exposed piglets. It is noteworthy that nerves from the exposed pigs showed less excitability in the conditioning-test response for which results in the rat were opposite, exhibiting increased excitability. Finally, when these pigs matured and breeding was attempted, they showed a poor success rate (8 pigs bred out of 22) as compared to the sham exposed animals (8 of 10), despite evidence for a greater number of attempts.

Thus, the teratologic pattern presented by the two breedings of the F_0 is entirely contradictory, while the data on functional status of the progeny shows a mixed pattern of performance changes.

Interpretation of these data is premature insofar as the final report is not yet available. The possibility of confounding factors in a study extending over so many months is a serious problem that cannot be fully controlled with even the utmost care to avoid infections, behavioral interactions among the animals, etc. Efforts to provide explanations of the results have cited the outbreak of a swine dysentery between the two breedings of the F_0 sows, but neither the dysentery nor its treatment are likely causes for the variable results that were seen.

Other Positive Results - The complete tabular listing of results (presented as Table V-2 in Phillips, Anderson and Kaune, 1981) also shows that signficant, replicated positive effects have been observed in several other tests:

(1) The righting reflex was found in fewer of infant rats exposed from conception to 8 days after birth as compared to unexposed controls.

(2) Motile behavior of the exposed rats was greater.

(3) Red cells parameters were altered in mice of the third generation exposed to 0.120 to 0.250 kV/m electric fields.

Conclusions from the Battelle Studies

Overall, the understanding of electric field bioeffects has been markedly advanced by these studies. At the inception of the project the literature was so seriously compromised by questions of dosimetry, artifact and improper procedure that it was difficult to accept the few data that indicated electric field effects. Now, in light of the small animal studies, it is apparent that several incontrovertible effects in laboratory animals can be attributed to 60 Hz electric fields that are presented for nearly continuous periods over times long in comparison with animal lifetimes, at effective field strengths of the order of 65 kV/m. It is also apparent that no major effects on a physiologic function have been observed, with the exception of the apparently major changes in metabolic functions of the rat pineal gland and in rat testosterone levels. Even so, effects on animal reproduction, health, morbidity, growth and development have not been significant and it is reasonable to conclude that these studies have not shown any effects that would be evidence for an assumption that human health would be affected by fields of approximately 1 to 10 kV/m.

On the other hand, the same data indicate effects for which mechanisms are not understood, and for which it is reasonable to presume a novel, subtle influence on cellular functions. If the existence of such a mechanism is assumed, it is then evident that much more understanding of these biological effects must be obtained before it is possible to conclude that the long term actions of slight influences is without harm to the human organism. In this regard, the evidence of effects linked to circadian rhythms is of special note, because many aspects of well-being depend upon synchronous operation of the biochemical rhythms of the body.

Inconsistent and inconclusive results from the study with swine raise the possibility of teratologic effects which are of special interest in light of reports of reproductive problems among Swedish switchyard workers (where the males are exposed).

It is also noteworthy that several key results from this body of data stand in reasonable agreement with the data from other laboratories, so that a slight, but growing basis now exists for scientific progress, particularly in the areas of behavior, sensory detection of the field, cell membrane effects, neurophysiology, and bone repair.

RESEARCH from OTHER LABORATORIES

Although the project at Battelle Laboratories is large and has been productive, there are many interesting and important studies that come out of other laboratories. Due to differences in research approaches by different scientists, this diversity is an important feature from which will come fuller understanding of the biological significance of the interactions seen so far. In the United States laboratories involved in 60 Hz research are found at the University of Rochester (physiology, neurochemistry and behavior); Veterans Administration Hospital, Loma Linda (neurophysiology, neurochemistry, mechanisms at the cell surface and behavior); Southwest Research Institute, San Antonio (primate behavior and exposure dosimetry); Environmental Research Administration, Research Triangle Park (neurochemistry); Tulane University, New Orleans (physiology); Pennsylvania State University (behavior, physiology and plant growth); University of Wisconsin, Parkside (reprodcutive & general physiology of protozoa, slime molds); Washington State University, Seattle (dosimetry); Los Alamos Scientific Laboratory, Los Alamos (microrganisms); Argonne National Laboratory, Chicago (physiology, behavior and biorhythmicity).

1. Overview of Experimental Results

There is now a modest and growing base of data from experiments with low frequency electric fields. Although there are data scattered over many values of electric field and frequency, there are clusterings of experiments at 100 kV/m, about the maximum practical limit for a laboratory system, near 10 kV/m, an easier voltage level at which to work, and one chosen at first for its similarity to the transmission line electric field strength, perhaps fewer experiments between 10 and 1 kV/m, and again a larger number of experiments in the range of 100 to 10 volts per meter that were stimulated by interest in the biological effects of an ELF antenna system proposed by the United States Navy (Anon, 1975; National Academy, 1977).

Many experiments have been performed with the explicit or implied hypothesis that because the nervous system functions at an electrical level, with continually changing electrical inputs to individual cells or whole brain structures, there might be an interaction of the electric field with nervous system function. Such hypotheses were stimulated by the initial reports of electric field effects on the health of substation employees in the U.S.S.R. (Korobkova et al., 1972, Asanova and Rakov, 1966). These researchers concluded that their observations showed a generalized alteration in central nervous system (CNS) function. Emphasis on possible CNS effects continues today in many research programs.

Some experiments have been based on the generalized physiological hypothesis that an electric field effect continued over a long period of time would produce a stress response in the animal. This response might alter cardio-vascular function, change immunity or alter various biochemical and physiological parameters.

The review that follows is not complete, but attempts to touch on those areas most important to the issue of HVTL health and safety. For additional material see, Bridges, 1975; Bridges and Preache, 1979; Anon., 1979a,b; Sheppard and Eisenbud, 1977; Dumanskiy, 1975; Provkhatilo et al., 1981; Watson, 1979; National Academy, 1977; Anon., 1974; Waskaas, 1981; Phillips et al., 1981.

The data obtained from physiology studies include those conceived from the point of view of classical toxicology (where agents act chemically or physically), or those that have attempted to take into account the unique aspects expected of the electric field interaction with biological systems. Because of the pervasive influence of the nervous system on all physiological functions, and in view of the reasonable hypothesis of greater electrical sensitivity for nervous system tissues that are already specialized to respond to electrical and electrochemical signals, many experimenters have focused on the role of neural tissues. At this time many of the best-described effects of 60 Hz electric fields do involve tissues of the nervous system. A major exception to this generality is found in the extensive body of research on stimulation of bone growth, where often the fields are pulsed magnetic fields that induce electric fields (of uncertain magnitude) in the tissues or cell cultures under study. Significant effects on bone repair in animals exposed to sinusoidal 60 Hz magnetic fields have also been obtained.

2. Neurophysiological and Neurochemical Studies

Neurophysiologic studies are generally conducted on small laboratory animals and cultured tissue, except for a few behavioral studies that use sub-human primates. Some early experiments with small animals had shortcomings in experimental technique, especially the occurrence of electric shock discharge, poorly established control groups or statistical promlem. But the most important practical difficulty is the uncertain extrapolation from animal to human exposure situations. These difficulties notwithstanding, the neurophysiological data seem to establish the principle that weak internal electric fields, can have effects on components of the nervous system including individual neurons, brain tissues, synaptic transmission in nerve fibers, and biochemical properties of the pineal gland. These results were obtained in experiments small animals exposed to effective electric fields of 65 or 100 kV/m in air (Jaffe, 1981; Wilson et al., 1982; Anderson, 1982) and in *in vitro* studies that introduce ELF fields directly to isolated tissue (Bawin et al., 1975, Bawin, et al., 1976; Bawin et al., 1978a,b; Blackman et al., 1982; Lin-Liu and Adey, 1982; Wachtel, 1979; Sheppard et al., 1980a,b; Bawin et al., 1981; Dutta et al., 1982), as well as an *in vivo* study (Adey et al., 1982).

Calcium Efflux in Neural Tissues - There has been considerable interest in one *in vivo* and a number of *in vitro* experiments that involve measurement of the exchange of calcium ions with the surface of brain tissue: "calcium efflux" studies. These studies establish the fact that weak fields could affect biomolecular structure in highly specific ways. The unique characteristic of the various observations by Bawin and Adey, Blackman, and Dutta, each with their co-workers, is the apparent restriction of effects to certain "windows" in frequency (maximum effect at 16 Hz) and field strength. The "frequency and power window" concept introduces a great deal of difficulty into the interpretation of experimental data, and particularly in the extrapolation of laboratory exposures to man. The window phenomenon was first observed in several in vitro experiments that showed a 10-20% alteration in the calcium exchange from cat and chick brain tissues exposed to radio frequency electric fields that are ELF-modulated at frequencies near 16 Hz (ELF/RF) (Bawin, et al., 1975; Blackman et al., 1979). The effective 16 Hz electric field strength is not known, although the upper limit is given by the magnitude of the carrier wave which produced an internal electric field estimated at 100 mV/cm (Adey, 1976). If it were of this magnitude, there would be little direct bearing on exposure to HVTLs where tissue level fields are about three orders of magnitude less, but the actual field strength depends upon the efficiency of demodulation. However, the mechanism for demodulation has not been well defined (Sheppard, Bawin and Adey, 1981).

There is no significant heating of tissue (Tenforde, 1980) and no known artifact associated with the ELF/RF form of field presentation.

Other experiments involve calcium efflux from chick brain hemispheres exposed directly to ELF fields of less than 100 V/m without use of the modulated carrier-wave technique. These studies also show windowed changes in the calcium efflux (Bawin et al., 1976). Recently, Blackman et al. (1982a,b) reported more extensive data that indicate strong windowing of the frequencies and field strength for ELF fields.

Adey et al. (1982) report changes in calcium efflux from the cortex of a living cat. The rate of calcium exchange oscillates over the course of an hours-long period of examination that included a 60 minute exposure.

Lin-Liu found a frequency dependent change in calcium binding to symaptic membrane (Lin-Liu and Adey, 1982). Effects were seen for 16 Hz modulation, but not for 60 Hz.

Few of the data referred to above involve exposure at 60 Hz, but Blackman et al. reported efflux effects at frequencies of 45 and 50 Hz (50 V/m) (Blackman et al., 1982b).

These data on calcium exchange have had a strong influence in establishing that physiological effects may occur, and in pointing out the existence of the windowing phenomena. As a result of the apparent success of this assay other studies which produced negative results have been reported (Shelton and Merritt, 1981; Merritt et al., 1982), but those data are not necessarily in contradiction, perhaps due to the pulsed waveform that was employed.

The calcium effect is windowed in frequency: In the ELF/RF studies maximal effects occur at 16 Hz modulation and are not detectable at frequencies that differ by a factor of two, nor is there any effect of the unmodulated carrier wave (Bawin, Kaczmarek and Adey, 1975). In the ELF-only studies a second window above 45 Hz seems to appear according to preliminary results reported by Blackman et al. (1982). In the ELF studies two amplitude windows have been observed at about 10 and 50 V/m (Blackman et al., 1982). The calcium that is available for exchange resides in the very superficial layers of the exposed tissue. Because of the slow (1mm/hour) diffusion rate for calcium ions in brain tissue, Bawin and co-workers argue (Bawin et al., 1978b) that measured effects involve mostly superficial Ca^{++} bound to the cell membrane surface. Experiments to investigate the influence of changes in the ionic milieu (Bawin, Sabbot and Adey, 1978) disclosed an apparent sensitivity to H^+ concentration that suggested competition of Ca^{++} and H^+ for binding sites, presumed to be along the glycoproteins that project from the lipid bilayer membrane into the extracellular space. Experiments with binding of La^{++} indicated a decreased efflux during exposure to the field, opposite in direction to the Ca^{++} results. This may be a reflection of differences in binding competition of La^{++} and H^+ in contrast to Ca^{++} and H^+ and, since La^{++} blocks the transmembrane Ca^{++} channels, the data suggest an effect that is primarily at the cell surface.

Further evidence of the amplitude sensitivity observed in these studies comes from the work of Blackman and Joines (1981, 1982) who found that effects could be observed with a 50 MHz carrier only if the effect of the frequency dependence of the dielectric constant was considered. This allowed an electric field strength of the same magnitude as when the 147 MHz field was used.

Dutta and co-workers (1982) report preliminary results on Ca^{++} efflux with cultured neuroblastoma cells of mouse or human origin. Once again a amplitude-windowed response was found using a 16 Hz modulated RF carrier.

The calcium data have raised several key points. Because of the widespread, essential neuroregulatory role played by calcium ions in many membrane processes, including the well known role of calcium in neurotransmitter release or the role of calcium in competitive binding to membrane macromolecules, the establishment of the action of weak ELF fields on calcium exchange suggests, but does not demonstrate, a vast potential for profound changes in brain function. Indeed, Adey (1976) found it surprising that there were not grossly observable effects of such fields. On the other hand, most of the data referred to are obtained from _in vitro_ studies with "freshly dead" tissue, and it may happen that homeostatic mechanisms have the capacity to neutralize the changes that occur when the living animal is exposed. (C.f., the oscillatory changes found in the _in vivo_ study, above.) Using the strong fields provided by the modulated-rf techique Adey did, however, find oscillatory changes in calcium exchange of the _in vivo_ cat cortex.

3. Electrophysiology Studies in Vitro

Wachtel (1979), Sheppard et al., (1980) and Bawin et al., (1981) reported preliminary evidence from _in vitro_ studies that electric currents can alter the excitability of neurons. Observations of pacemaker activity in neurons of the _Aplysia_ ganglion show that extracellular currents can interfere with the rate of firing in a manner that depends strongly on frequency. The greatest sensitivity of these invertebrate neurons occurs at frequencies near the natural firing rate of about 1 Hz. The manner in which the weak extracellular current affects neuronal excitability is not clear. Scaling to a mammalian system on the basis of equal current density would require electric fields much greater than could be generated by a HVTL, but if the effects reported for tissue-level fields of 10 mV/cm, to as low as about 0.5 mV/cm (Sheppard et al., 1980) are scaled according to electric field strength, the effects in HVTL-strength fields may be related to those seen in these studies.

Electrophysiologic data from mammalian tissue were reported by Bawin et al., 1981. Hippocampal neurons were tested in vitro for their response to a pulse that causes synchronous firing of a large number of coupled neurons. The effects on neuronal excitability observed are similar to those known from prior research that uses electrodes in contact with the tissue. Extracellular fields of about 10 mV/cm (rms) at 60 Hz (Bawin et al., 1981; 1982). produce effects that include a potentiation of the collective cell firing that lasts for many minutes. These studies are conducted at current densities and electric field strengths greater than those that would be found in the tissues of field exposed animals or humans, but a threshold for effects has not been determined.

In both the mammalian and invertebrate studies the results show that the tissues have not been damaged, but the functional changes that occur may be related to nervous system effects observed in studies of intact animals. If these studies involve a mechanism significant at lower current densities, or if the mechanism is best measured by electric field strength rather than current density, the results found at the tested field levels may apply to HVTL exposure conditions.

4. Effects on Cultured Cells

Frazier and co-workers (Frazier et al., 1982) reported preliminary results of several experiments with cultured tissues. Mammalian ovary tissue (CHO-K1) was grown in the electric field induced within a toroidal chamber by a 60 Hz magnetic field. At 3.7 V/m (37 mV/cm) no effects were observed on cell viability, growth and mutation rate, but an 8 hour exposure at this level was correlated with reduced cell survival. An effect on cell plating efficiency, presumably an expression of an alteration in the cell membrane surface, was found for 60 Hz fields greater that 0.7 V/m (7 mV/cm). As for the above-mentioned electrophysiology studies, these field levels are substantially greater than the tissue level fields to which the human body is exposed during exposure to a large HVTL electric field. However, the magnitude of these fields is within about one order of magnitude of the maximal HVTL-induced fields.

An extensive series of studies with the slime mold Physarum polycephalum has shown frequency-dependent effects at about the same level of electric field strength as in the preceding cell culture and electrophysiology experiments. In addition, separate effects of electric or magnetic fields were seen. In the initial studies (Marron et al., 1975; Goodman et al., 1976) both electric (7 mV/cm) and magnetic (2.0 G) fields were applied at 45, 60 and 75 Hz with significant effect on mitotic rate (observed over a period of months), protoplasmic streaming and cell respiration. Moreover, separate magnetic or electric fields of similar magnitudes and frequencies had effects that were somewhat less than those seen when combined fields were used (Goodman et al., 1979).

Other recent reports suggest that stronger magnetic fields can effect cell growth in culture. Tabrah et al. (1978) found greatly reduced growth rates, higher cell mortality, cytomorphologic changes, and altered oxygen uptake in a unicellular organism exposed for 49 hours to 60 G (or 100 G in the respiration study) at 60 Hz. These solenoidal fields had a gradient of 2 G/cm. Studies with dc magnetic gradient fields showed no effects of field exposure

Raman et al., (1980, 1981) reported inhibition of growth in E. coli bacteria exposed to magnetic fields of 600 Hz at field strengths of 2 to 30 G for periods of 50 h or longer. Experiments conducted at 60 Hz were negative, perhaps reflecting the much lower level of induced electric field at the lower frequency. The authors suggest that the field has a direct effect on the flagellar apparatus of the bacterium, but the biophysical details are not presented and do not appear obvious.

Unfortunately, both of the preceding studies fail to define the magnitude of the induced electric field that would be found in the medium due to the alternating magnetic field.

Dixey and Rein (1982) used a pulsed magnetic field (1.6 to 8.5 G) to produce electric fields of 0.38 or 0.19 mV/cm in a medium containing a clonal culture of cells of neural origin (rat PC12 neuroblastoma). Neurotransmitter release (^{3}H-NA) following a 13 minute exposure to the pulsed field was significantly elevated above the control levels. The field-related increase was abolished when magnesium (15 mM Mg^{++}) was added to the medium, to indicate that the magnesium blocked transport of the extracellular calcium ions required for the stimulation of transmitter release. By inference, the primary step in the field-produced change in transmitter release is an effect on calcium binding, possibly related to the effects observed in studies of calcium efflux by Bawin et al. and Blackman et al. (see above).

5. Neurophysiologic Studies in Small Animals

Blanchi, et al. (1973b) observed significant changes in the electrocardiogram and electroencephalograph patterns of animals exposed to a 100 kV/m 50 Hz electric field. The EEG activity of guinea pigs exposed for one half hour showed: 1) The appearance of a slow fequency, high amplitude wave that persisted throughout field exposure; 2) An increase in the number of spindles during the field exposure; 3) A short-term desynchronization occuring soon after application of the field. In addition, a short period of desynchronication was often seen shortly after the field was turned off. These effects were not seen in a similar study at the Battelle laboratories (Hilton and Phillips, 1980; see above).

6. Blood Cell Counts and Serum Chemistry

Field effects on peripheral blood composition and biochemistry were studied by numerous investigators (Phillips et al., 1979, Phillips et al., 1981, Blanchi et al., 1973a, Hauf, 1974, Noval, 1976) Although effects are usually small and not often replicated in a subsequent group of animals, overall the data suggest a variable pattern of field-related changes in several white blood cell populations, with particularly suggestive evidence for a prompt effect on neutrophilic and eosinophilic cells and effects on thrombocytes and reticulocytes. The data for blood plasma components (lipids, proteins, enzymes, etc,) also present no consistent picture of physiologic or pathologic changes despite the occurence of statistically significant results in several studies. Generally, the changes in the blood picture involve small deviations so that the values are still within physiological norms. Because the mechanism by which these effects occur is not known, the health implications of the changes cannot be evaluated, but in and of themselves they do not represent harmful changes.

7. Effects on Bone

Well-documented effects occur in bone tissues exposed to ELF electric fields. In the case where electric fields are induced by a pulsed magnetic field, the effective ELF component is not easily determined, and is probably comparable to a pure ELF exposure at large voltage gradients (10^5 V/m or more).

Research into the bioelectric properties of bone is now more than 25 years old (Fukuda, 1957). After initial research that showed bone growth is altered by direct currents of several microamperes delivered by implanted electrodes (Becker and Spadaro, 1972), Bassett, et al. (1974a) demonstrated that a pulsed magnetic field (65 or 1 Hz repetition rates) also could produced changes in bone growth. Many thousands of persons suffering from bone fractures that do not heal by themselves, and particularly those with certain bone diseases, have been successfully treated with pulsed magnetic fields to promote bone union (Bassett, et al., 1974b; Pilla, 1977). In two studies of fracture repair in sinusoidal 60 Hz electric fields (Marino et al., 1979; McClanahan and Phillips, 1981) a retardation of healing was seen. Marino et al. investigated the rate of fracture repair in rats with surgically induced fractures. Retarded repair rates and altered micro-anatomy were found following exposures to 60 Hz electric fields of about 15 kV/m. McClanahan and Phillips also found a slower rate of fracture repair -- but eventually an identical final state of repair was found in rats that were continually exposed at 65 kV/m (effective field strength). (See above for more discussion of this latter study.)

8. Effects of Pulsed Magnetic Fields in Other Tissues

Experiments in several test systems indicate that pulsed magnetic fields can affect growth in other tissues as well as in bone. Furthermore, these studies indicate that only certain frequencies and induced current levels effective, thus defining "windows" for the biological response characteristics. The test system that has proven most rapid and useful assays bone growth (via $^{45}Ca^{++}$ uptake) in chick-embryo limb rudiments exposed to the pulsed magnetic field created with a pair of Helmholtz coils (Fitton-Jackson et al., 1980). To examine for a possible magnetic field effect, an experiment with chick limb rudiment was performed in which magnetic field exposure to the tissue was attenuated to a low, and presumable insignificant, level by a magnetic shield, while a control limb was exposed to the magnetic field. Both samples were exposed to the same induced circulating electric current. When compared with unexposed tissues, the growth increment in either of the exposed tissues was the same. The biologically effective modality is clearly the charge movement within the medium, rather than a magnetic influence on the tissue. Further studies with the chick limb rudiment system disclosed the existence of a sharp frequency and amplitude dependence that showed both lower and upper bounds and so defined a window within which effects occur. This "window" is in contrast a "threshold" for which effects occur only above a certain level. The window can be derived from a LaPlace-transform analysis of the frequency spectrum (Pilla and Margules, 1977). The mathematical analysis depends on the pulse parameters of width, repetition rate, number of pulses per pulse train. Based on this analysis, the biological data seem to show that growth effects depend only upon the amplitude of low frequency portion of the spectrum.

This analysis ignores the largest component of induced electric field which is produced by the swift rise and fall of the magnetic field at the pulse edges, and only considers the decay of the magnetic field according to the circuit inductance, and resistance, pulse duration and repetition rates. Because repetition rate also describes the larger electric field produced by the swiftly rising or falling pulse edge, it is not clear how one should calculate the effective ELF electric field strength that is biologically significant.

Based upon an electrochemical theory of charge transfer at the membrane interface, Pilla and Margules (1977) argue that the pulse-edge produced fields are too fast to have biological effects and they calculate that there is an effective current density of about 1 uA/cm^2 which corresponds to an electric field of 0.1 mV/cm, assuming a medium resistivity of 100 ohm-cm.

The electric field related to the pulse induces a current density into the test tissues that can be greater than the (maximal) current density of approximately 0.3 uA/cm^2 that is induced in a human being in a 10 kV/m 60 Hz HVTL electric field. It is important to determine the effective current density in these magnetic field studies more accurately in order to know if the mechanism for stimulation of bone growth occurs at field strengths similar to those of environmental interest. Evidence for the effect of pulsed magnetic fields on surface biochemical processes was shown in bone by Luben et al. (1982) where in vitro osteoblasts were found to have increased sensitivity to stimulation by parathyroid hormone (PTH) following exposure to a pulsed magnetic field. Strong evidence for an effect at the cell membrane is presented by a contrasting study that showed no field effect on stimulation by Vitamin-D, which acts at the cell nucleus.

Jolley and co-workers (1982) observed significant changes in both the production of insulin and in calcium efflux from isolated pancreatic cells exposed to a magnetic field pulsed at 72 Hz.

Smith (1974) and Smith and Pilla (1979) investigated the influence of pulsed magnetic fields on the regeneration of newt limbs as a function of the pulse repetition rate. At some repetition rates regeneration was stimulated, while at others regeneration was inhibited when compared with the controls.

Sisken (1975) and Sisken et al., (1980) have applied pulsed magnetic fields to a neural culture prepared from chick trigeminal nerve and observed alterations in the extent of neurite growth.

Delgado and co-workers (Delgado et al., 1982) report severe disturbances in embryological development of chicks exposed for 2 days to a 12 to 0.12 uT (0.12 to 0.0012 G) pulsed magnetic field with repetition rates of 10, 100 and 1000 Hz. Unlike the controls, where malformed embryos were observed about 10% of the time, the exposed eggs showed malformation rates of greater than 50%. Effects were found to be dependent on pulse repetition rate and magnetic field strength in a manner that suggests a windowed response with maximum effects at 100 Hz at 1.2 uT. The magnitude of the induced electric fields cannot be determined from the report.

In summary, the electric fields induced by pulsed magnetic fields of an uncertain effective electric field strength and uncertain spectral distribution (within the ELF range) are capable of strong interaction with, and manipulation of, cell membrane properties. Consequent changes in tissue largely involve levels of growth and secretion, but now appear to include interference with normal embryogenesis in the chicken.

9. Physiology Study with Mice in a Strong 60 Hz Magnetic Field

Fam (1981) conducted experiments with mice exposed for 23 h daily over a period of one week to an intense 60 Hz magnetic field of 0.11 Tesla (1100 G). Statistically significant effects on growth and water cosumption were observed, but measures of blood proteins, white cell counts and *post mortem* histologic examinations found no further evidence for an effect of the fields. In a related study, 6500 hours exposure of two male mice disclosed no significant effects on the progeny with respect to survival and the number of births per litter.

10. Sensory Phenomena with an ELF Field

Kalmijn (1974) has explored the electroreceptive properties of various elasmobranch fish that show behavior (such as sensing prey) that involves a response to weak gradients of as little as 10^{-6} V/cm in seawater. Bullock (1973) discusses electrosensing and electrocommunication in other fish to demonstrate the existence of a range of field sensitivities and a varied distribution of species-specific signals using pulsed signals in the ELF range. The data from fish illustrate the existence of extraordinarily sensitive electroreceptive capabilities in some species, particularly where there has been evolutionary adaptation of sensory organs (e.g., the Ampullae of Lorenzini), but the neurophysiologic mechanisms are not clear. The abilities of many species to navigate, especially over global distances during migration, seems to involve numerous species-dependent cues. In salmon and eels these cues may include electroreception of information as may result from the movement with respect to the geomagnetic field of currents of water to produce a small, oriented electric field in the ocean (Rommell and McCleave, 1972; 1973a,b).

In birds, cues including magnetic field direction seem important (Keeton, 1972; Walcott, 1974), and in bees, where permanent magnetic materials have been found (Gould et al., 1978) similar magnetic sensitivity exists.

In man, ELF magnetic fields of moderate intensity (about 100 gauss or more) produce the visual phosphenes that were discussed previously.

11. Growth and Development

Many studies now begun and many completed (Phillips, et al., 1979, 1981; Rosenberg et al., 1981; Marino, et al., 1974, 1976; Seto, 1979; Noval, 1976; Mathewson, 1977; LeBars and Andre, 1976; Cerretelli and Mulagati, 1976, 1979; Fam, 1980; etc.) provide evidence that effects on growth and development do not occur with consistency and it is likely that an electric field alone is not sufficient cause for such effects.

Hansson (1981a; 1981b) found severe effects on young rabbits exposed in a switchyard environment that involves a strong electric field (50 Hz). (See immediately below.)

12. Developmental, Ultrastructural and Biochemical Effects

An important research study in Sweden found that rabbits exposed in the 14 kV/m field of a 400 kV (50 Hz) substation (Hansson, 1981a; 1981b) showed large, deleterious changes in cell structure, animal growth and development. There was up to a 50% difference in weight between the exposed rabbits and either of the two control groups: (1) animals screened from the field by a Faraday cage, or (2) animals kept outside the substation area entirely. For both these rabbits and animals exposed in the laboratory, a number of specific pathological changes were found in the Purkinje cells of the cerebellum. Ultrastructural and biochemical tests showed specific, localized changes in the cytoskeleton of brain cells, and alterations in two glial proteins (S-100, GFA).

In rabbits, Hansson reports the changes included an abnormal alteration of the endoplasmic reticulum to form lamellar bodies, not seen in normal tissue, although exposure to some chemicals can produce the same changes. (Artifacts of the prepartion for electron microscopy could also be suspected, but the author's techniques appear to control for such problems.) The Purkinje nerve cells of the cerebellum of these brains also showed a reduced number of mitochondria, reduced arborization of the dendritic branches, and an absence of hypolemmal cisterns.

The reported changes represent major alterations in cellular structure for which serious dysfunctional changes in the cells would be expected. It should be noted that exposure of the rabbits at 14 kV/m represents an exposure to humans at considerably lower field strength. In consideration of the marked behavioral and ultrastructural changes in rabbits, it would be remarkable that major pathologic changes in other animal species are not known, were it not for the data obtained in the companion laboratory study where the growth stunting was not seen in laboratory-exposed animals. This discrepancy is not explained except for speculation on a possible synergism of electric fields with the outdoor environmental conditions.

13. Reproductive Behavior

Studies of reproductive function have been carried out at many field strengths (Knickerbocker, et al., 1967; Marino, et al., 1976a; Phillips, et al., 1979) with no evidence of a consistent electric field effect in rats and mice, but in miniature swine (see above) teratology and breeding problems may exist.

14. Cardiovascular System

The evidence for changes in cardiovascular function is limited and contradictory. At this time the data from animal studies (Hilton and

Phillips, 1980) do not support the occurrence of such changes while the data from humans (Asanova and Rakov, 1966; Hauf, 1974) suggest that if effects do occur it is only after chronic exposures.

15. Effects on the Immune System

In consideration of the pattern of slight effects on white cell populations it is of special importance to evaluate the immunocompetence of electric field-exposed animals. Experiments on the ELF field effects on immunocompetence, as determined by several mitogen stimulation tests with mice (Phillips et al., 1981) were negative, but these studies were done at very low field strengths (see above).

Other studies by Phillips, et al. (1979, 1981) indicate no decrement in immune response to an infective agent, but once again a weak field was used.

Lyle et al., (1981) found significant effects on the cytolytic ability of lymphocytes that were exposed to a modulated radio frequency field. Significant decrements in cytolytic capacity were observed at 60 Hz, and to a lesser extent at other frequencies.

Fischer (1973) reported significant changes in immune status for animals exposed to a strong (24 kV/m) electrostatic field. Further research is indicated before a firm conclusion is possible.

Overall, the evidence is that animal morbidity and mortality in chronic exposures is unaffected, suggesting that immune response is generally unaffected, but more research is required.

16. Genetic Effects, Cellular Reproduction

Combined ELF magnetic and electric field affect mitotic rate in slime molds (Goodman, et al., 1976) exposed to electric fields that are large in comparison with the tissue level electric fields of ELF-exposed whole bodies. Studies in Drosophila (Mittler, 1972; Bender, 1977) indicate no effect although an early study (Coate, et al., 1970) did suggest effects. Marino, et al. (1974) report chromosomal abberations in tumor cells injected into mice exposed to an electrostatic field and they also speculate (Marino, et al., 1976a) that genetic effects underlie the results of a multi-generational mouse study. Other studies (Knickerbocker, et al., 1967; Krueger et al., 1972; Seto et al., 1979; 1982) show no effect on reproductive functions in whole animals. It is clear that no genetic effects are demonstrated for ELF electric fields at a field strength relevant to HVTLs, but contradictory findings of teratology in swine, and chromosomal and birth defects in Swedish switchyard workers indicate the need for further study.

IV ELECTRIC SHOCKS in STRONG ELECTRIC FIELDS

In regions of high electric field strength, objects at different positions (especially at different heights above ground) can have large potential differences. If the objects are small, there can be a noticeable transient discharge in those cases where there is adequate insulation and the object is high enough above ground to achieve a high voltage. This charging may be repeated each half of the electrical cycle but the total current flow will be small if the object is small.

If the object is large and the human body becomes the pathway for current to ground, electric currents (of the order of 10^{-4} to 10^{-3} ampere) can flow steadily. The investigation of these effects has identified two exemplary cases in which significant shock currents exist: 1) a long ungrounded metallic fence running along the right of way; and 2) a large vehicle beneath the conductors and effectively insulated from ground. The short circuit current that flows when the charged object is grounded depends upon the capacitance to ground of the object and the open-circuit voltage to which the object is charged when disconnected from ground, according to the relation:

$$I_{sc} = \omega C V_{oc},$$

where ω is the angular frequency, V_{oc} is the open circuit voltage, and C the capacitance to ground of the object (Deno, 1975). For humans standing on the ground with arms at the side of the body in an electric field of frequency f, the short circuit current (amperes) is given approximately by the empirical formula:

$$I_{sc}\,[A] = 5.4\ 10^{-9}\ h^2\ E\ (f/60),$$

where h is the person's height in meters (m) and E the electric field strength in volts per meter (V/m) (Deno and Zaffanella, 1982, p. 365).

(The preceding reference also gives more detailed formulae for other practical exposure situations.) Thus, in a 10 kV/m 60 Hz electric field a person 1.7 m tall carries a short circuit current of about 160 uA. Deno presents data of typical capacitances for objects which range from 700 pF for a small vehicle to several thousand pF for buses and large trucks and about 1000 pF for a 150 meter fence. Under the assumptions presented in the foregoing reference, the short circuit for the fence could be as great as 2.2 mA if located in a field of 5 kV/m. Zaffanella and Deno (1978) measured short circuit currents of a farm tractor, jeep wagon and school bus. In a 10 kV/m electric field these vehicles conducted 0.6, 1.1, and .9 mA of current to ground, respectively. Although these shock currents are of appreciable magnitude they do not present a hazard to adults. Adequate data for shock hazards in children are not available and although the let-go threshold in children is often cited as 4.5 mA (60 Hz), there are scant data to support this figure (Dalziel and Lee, 1972; Keesey and Letcher, 1970). Scott-Walton et al. (1979) present an excellent review of this issue as it relates to the uncertain margin of safety between let-go levels and thoracic tetanization levels in children.

Good engineering practices dictate the mitigation of shock hazards by careful grounding of fences, gutters or other long metallic objects in a strong electric field. It is unlikely that a hazardous situation would occur with the vehicle parked under the line because under most circumstances there is a substantial leakage conductance between ground and the vehicle tires through which most of the short circuit current would flow. The elimination of annoying or dangerous shock currents requires careful engineering consideration for vehicles and buildings near a high voltage line, but such shock effects are outside the scope of this document.

As discussed above, an insulated object can become electrified at high potential in the presence of a strong electric field and when contact is made with such object by a reasonable well grounded person the electric charge on that object will rapidly flow toward the person and then to ground. Similarly, if a person is raised to a high potential, the discharge of his charge will occur upon touching a grounded object. This last situation resembles the well known experience of receiving a shock upon touching a grounded doorknob after walking across a rug, especially when the humidity is low so that the electric charge built up by friction is not quickly dissipated. The amount of charge stored on the object at a given voltage determines the object's capacitance. For example, a sphere of radius r, at a height h, above ground has a capacitance to ground of:

$$C = 4\pi\varepsilon_0 h/(1/r-1/2h),$$

where ε_0 is the dielectric constant for air. Depending upon the type of contact made between person and object, instantaneous values of the contact resistance, and the impedance to ground of the person or object, the transient current can reach different magnitudes and produce different degrees of sensation. Zaffanella and Deno (1978) present data taken under various circumstances that indicate peak currents of up to 20 amperes can flow for a few microseconds when a person draws a spark discharge from an object with a hand-held metallic key, but the peak currents are an order of magnitude smaller if the finger is used for contact. The energy content of spark discharges obtained from a carpet are found to be similar to those in a 10 kV/m electric field with the important exception that the AC field continually recharges the electrified body so that repeated frequent sparks are possible, whereas one must take several steps on a carpet to re-electrify the body. Data from humans exposed to spark discharges of varying intensity show that 50 percent of the population sampled perceived spark discharges in a field of 2.7 kV/m and 50 percent of the population found the spark discharges annoying at 7 kV/m. To obtain these data persons standing in electric field touched a metallic post with the finger, and it is assumed that their capacitance was of the order of 170 pF (Zaffanella and Deno, 1978). Much smaller shock currents can occur at the surface of the body due to potential differences built by between skin and certain types of clothing or due to the potential differences between parts of the body and vegetation which one might contact. Additionally, the charging of hairs at the body's surface can produce a sensation due to the slight motion of these sensory organs in an electric field.

The sensations that result from such microshocks or hair stimulation due not appear hazardous (except insofar as they may produce a startle reflex that could induce an accident), but they may be highly significant in the evaluation of effects attributed to the fields. This document does not address the possible health effects of such microshocks or transient spark discharges.

V FIELD INTERFERENCE with CARDIAC PACEMAKERS

An implanted pacemaker is an electronic device which artificially stimulates the heart, thus making it possible for persons with certain heart diseases to lead relatively normal lives. About 170,000 persons in the United States (< 1% of the total population) currently use cardiac pacemakers, and of these, one-third are pacemaker dependent (Bridges et al., 1979). Although pacemakers are susceptible to many forms of electrical interference, no catastrophic situations resulting from ambient electromagnetic fields have been reported. Results of laboratory research in animals (Bridges and Frazier, 1979) have confirmed that widespread interference effects associated with 60 Hz transmission lines do not constitute a problem to the vast majority of pacemaker patients. Absolute safety is not assured under all circumstances due to uncertain electrical properties of each of the many different electronic ciruits and packages used by the manufacturers. Sensitivity is also affected to a great extent by the choice of lead placement made by the surgeon.

When exposed to an interfering electrical signal, the pacemaker circuitry switches to the "reversion mode" in which stimulating pulses are output regardless of the heart cycle. Operation during brief periods under this condition is reportedly acceptable (Bridges and Frazier, 1979).

There seems to be incomplete agreement among cardiovascular specialists about the existence and seriousness of the problems associated with prolonged operation in this mode (Scott-Walton, 1979).

Pacemaker reversion can be brought about via three mechanisms (Bridges and Frazier, 1979):

1. Direct coupling of ambient electric field (typical threshold range: 3-600 kV/m).

2. Transient coupling of ambient electric field through vehicle leakage current ("microshock") (typical threshold range: 60 V/m-60 kV/m).

3. Household appliances leakage current (typical threshold range: 40-6000 uA).

Thus, for a limited category of pacemaker patients, direct coupling to fields in the range above 3 kV/m may cause reversion.

The effects of current carried through the body as might occur when touching a vehicle under a HVTL, can cause reversion under the most sensitive set of circumstances at a field level of 0.06 kV/m, involving the worst-case device, worst-case electrode style and a very large vehicle (a semi-tractor trailer). With the most sensitive device even the small current from a sedan parked (with very high insulation to ground) in a region of 0.4 kV/m may cause reversion. The apparent hazard is slight, since the person would have no reason to continue to hold onto the vehicle to maintain the interference condition, and in practical circumstances the vehicle to ground insulation required is not obtained, nor is it likely that the person would be very well grounded by his footwear.

The degree of safety may be expected to improve as newer designs that take electric current problems into account are used in preference to older designs. Since cardiac patients are unlikely to be exposed during long periods to rights-of-way field levels, and since typical household appliances leakage current lie in the range between 2 and 200 uA, it may be speculated that HVTL interference with pacemakers, if any, would occur infrequently in comparison with interference by household appliances. It is uncertain if all instances of reversion would be harmless, i.e., would not result in cardiac fibrillation, which would be fatal without immediate medical intervention.

VI INTERACTION MECHANISMS

1. General Considerations: Macroscopic and Microscopic Theories

Theoretical understanding of the biological interactions at 60 Hz and other ELF frequencies has addressed these questions:

1. What portions of the body surface are sensitive to electric fields?

2. How do surface receptors respond to the electric field?

3. What regions of the body interior are sensitive to induced current densities?

4. How do cells respond to the electric field or current density that exist in the extracellular medium?

5. Does the cell respond at its surface or is the small amount of current crossing the membrane of significance?

Certain electric field bioeffects are now established well enough that some progress in theoretical understanding is under way. Overall, the development of the theory for ELF effects by electric fields of 100 kV/m or less is in the very early stages of developement. The most that can be said for the models suggested to date is that they provide guidance for the eventual detailed quantitative theories that are a necessary future development. The major approaches are outlined below.

2. Models of Interactions with the Nervous System

Generalized models for an interaction with the nervous system may be proposed on the basis of the overall transductive and amplification properties of nervous tissue. Because the elements of the nervous system perform in a highly nonlinear fashion, small amounts of energy may, through a hierarchy of electrochemical events, produce significant electrical signals suitable for long-range propagation within the nervous system.

A great difficulty of modeling ELF electric field effects is found in the recognition that the very first stages of transduction must themselves be highly nonlinear, that is involve the collective properties of a macromolecular structure. Moreover, the ELF electric field interaction would have to maintain potency in the midst of other electrical activity (such as the synaptic events, extacellular fields) that may be of greater magnitude but which act over very short time intervals.

3. Physical Chemistry Considerations

In principle, an electric field of sufficient magnitude could have a direct effect on the free ions in the extracellular milieu, by electric field effects on the charge portions of biomolecules, or by interactions with dipole or even higher moments of molecular electronic structure. In general, the orientation of biomolecules is an important property upon which many functional characteristics of biological systems depend. However the internal electric strength is approximately one million times less than the electric field impinging upon the outside of the body, and it is quite clear that the very small internal electric field cannot effect covalent molecular structure or the electrostatic bonds between molecules, nor can there be direct effects on steric structure.

4. Sensory Stimulation: Non-specific Stress

With reference to experiments in whole animals, Phillips et al., (1981) suggests that effects may be due to a low-level chronic stimulation of the rat sensory system, or due to a chronic state of stress, as first suggested by Marino et al., (1974). Evidence linked to the former model comes from the behavioral studies that show rat perception in fields as low as 4 kV/m and aversive behavior in fields above 50 kV/m. There appears to be no physiologic data to support the stress hypothesis. Finally, Phillips also suggests interactions may occur at the level of the cell membrane surface.

5. Biophysical Coupling

The current flow produced by electric fields in the body is small when compared with currents associated with action potential propagation in axons. However the electric field characteristic of brain waves is perhaps no more than one order of magnitude larger than the internal electric field in the brain of a man subjected to a 10 kV/m electric field (Elul, 1972).

In his original consideration of ELF electric field interactions with neural cells Schwan (1972) demonstrated that neural membrane potentials could not be affected by even the largest electric fields that can be created in air as a result of a transmembrane current. These calculations were made with a wide range of assumptions for cellular shape and cellular electrical properties. Later, Schwan (1977) added further considerations based upon cell size, the low frequency capacitance of cells and the large number of fixed charge sites associated with an extended membrane surface structure. He concludes that although high frequency fields cannot be coupled effectively into membranes, the anomalous properties at frequencies below 100 Hz, suggest a possible means for a novel transduction mechanism.

Adey (1977) suggests that it is important to take into account the possibility that one cell may influence another in brain tissue through modulation of their shared electrochemical environment. This influence may be by altered cationic concentrations in the extracellular medium, or by a change in the binding of opiods and other peptides at receptor sites on cell surface glycoproteins, or by a possible susceptibility of the individual neuron to the weak oscillating electrochemical field that can be recorded as the electroencephalograph signal. The source of the EEG field appears to be "leakage" from the multitude of fine dendritic branches that spread from the small cell body of typical cerebral neurons. Adey recognizes that the initial stimulus is weak so that the response of the tissue must involve a cascade of intracellular processes at far higher energy levels which implies a series of amplification mechanisms before or during the transmembrane coupling of the initial stimulus.

Generally, one can compare the energy in the signal with the thermal energy of matter at 37C which is about 0.025 electron volts. The naive calculation shows that to achieve the corresponding energy density in water at low frequencies would require an electric field of millions of volts per meter. Bawin and Adey (1976) note that although it appears thermal noise is substantially larger than the tissue components of imposed electric fields, the cell surface in the region of the counterion layer can act as a low pass filter so that the effective noise noise voltage field would be of the order of 10^{-8} V/cm over a band from 0 to 100 Hz. This value is in close agreement with observed sensitivities for the most sensitive examples of ELF electric field detection found in marine vertebrates, and perhaps applicable to birds and mammals.

Sheppard and Adey (1979) have made specific use of the cell surface polarization phenomenon to suggest an alteration in the momentum spectrum of colliding ions found near the membrane surface.

6. Effects on Membrane Proteins

Cain (1980) proposes that the extreme sensitivity of membrane ionic channel proteins to small perturbations in the membrane electrostatic field may be sufficient to bias the probability of channel conduction in a sufficiently large AC electric field. His model suggests that oscillating electric fields of sufficient magnitude can produce a DC shift in the state of the channel voltage sensor with the prediction that increases in amplitude of the applied field tend to bias the system toward the situation where both open and closed states are equally probable.

7. A Model for Bone Tissue

Although nerve cells are important, bio-electricity plays an important role in the cellular function of bone cells and appears to influence lymphocytes and pancreatic islet cells (see above). In consideration of the beneficial effects that current densities of the order of microamperes per square centimeter have on the healing of fractured bone, Pilla has developed a model for electrochemical information transfer at membrane surfaces (Pilla, 1980). In his model, nonspecific electrostatic interactions that involve hydrated or partially hydrated ionic species produce a minimal perturbation to the molecular structure at the membrane surface interface with the aqueous surrounding fluid. The net change in charge configuration produced is too small for the production of electrophoretic or dielectrophoretic effects, but at those portions of the interface where a divalent cation is membrane-bound there will be dielectric and electrostatic interactions that depend upon the concentration and diffusion coefficients of the adsorbed ionic species, and secondarily depend upon the ness of the diffusion layer, and other, kinetic, properties of the membrane surface region. In this manner the binding of ionic species of low aqueous concentration which can contribute to the overall relaxation of charge changes at the membrane surface. The essence of Pilla's model is that specific surface adsorption is expected to exhibit a significantly longer relaxation time than dielectric or electrostatic interactions due to the number of aqueous and membrane steps involved, so that the characteristic time for adsorption may be in the range of 10^{-4} seconds.

VII FINDINGS & RECOMMENDATIONS

1. Factors Influencing Estimates of the Risk from Chronic Electric Field Exposure

The key issues in the analysis of the scientific data bearing upon biological effects of 60 Hz electric fields are (1) whether biological interactions, apart from shocks or peripheral sensory stimulation, are reasonably certain, and then if the answer is "yes", (2) a determination if interactions are likely to produce hazardous alterations in particular tissues, or to have an effect on the nervous system that disrupts normal physiological function in a subtle fashion.

A conclusion on the likelihood for hazardous effects of long-term exposure to 60 Hz electric fields is arrived at in the context of many factors peculiar to electric field bioeffects, as currently understood. Many of these factors are unique to the electric field interaction and for this reason it is important that the judgment of potential risk be made with an understanding of the significance of each of the following:

1. Biological effects at electric field strengths relevant to human exposure near HVTLS have been demonstrated in animal research. Laboratory animals exposed to 60 Hz electric fields show effects in selected behavioral responses; selected physiologic or metabolic processes in glandular, bone, and nerve tissues, and in effects on the morphology of some cells of the CNS.

2. Laboratory studies suggest that effects on circadian rhythmicity are possible at relevant field strengths.

3. *In vitro* laboratory data calculated to correspond to field strengths somewhat in excess of transmission line electric fields establish that interaction with neurophysiological and bone growth processes

may occur. Extrapolation to the level of transmission line electric fields and evaluation of the pathological impact have not been done.

4. Less certain laboratory data indicate possible weak effects on blood cell counts, growth and development and there are inconclusive data conerning teratogenic and weak carcinogenic changes related to the fields.

5. Scaling from the electric fields used in animal studies to an equivalent human exposure is highly uncertain. Better scaling requires (1) advances in the detailed dosimetry of the body interior and exterior and (2) determination of a mechanism of interaction and its site.

6. Electric field interactions may not follow the models developed for toxic chemicals, physical factors, ionizing radiation, non-ionizing radiation or infectious agents insofar as the dose/response relation may not have a simple functional form (linear, logarithmic, or exponential) that is applicable over a large range in electric field strength. Unlike studies with toxicologic agents, the effects at high levels in the laboratory may not scale to the effects that occur in an entire population exposed at lower levels.

7. *In vitro* studies indicate that frequency and field strength windowing of the response are important considerations. The interactions with electric fields may occur only at certain field strengths. The dose response curve for electric fields may show discontinuous regimes of "effective" and "ineffective" field strengths. Within the "effective" regimes the response may be nearly 100% of maximal effect, with relatively abrupt transitions to "zero" effect. In this case, negative experimental results obtained at a strong but ineffective field strength may not indicate absence of effects in a weaker field.

There are now several experimental results consistent with this hypothesis. The possibility that windowed responses occur in living organisms, while not proven, must be considered a realistic possibility.

There is no precedent for dealing with this unusual form of interaction in other environmental problems, and until the extent of windowing is established, no regulatory schemes designed for this problem need be invented. However, the recognition of this potential problem is one input into the judgment-forming process which establishes the need for a cautious attitude.

8. In like manner, electric field interactions may not follow the models of chemical toxicology etc. insofar as the dose/response relation may not have a simple functional form for the frequency response of particular tissues or for the response of the organism. The frequency-windowing phenomenom is at about the same primitive stage of development as the field strength-windowing phenomenon and possesses the same disruptive influence on attempts to predict the nature of electric field interactions or to argue from experience with other environmental agents.

9. Biological effects may occur without significant health effects.

10. Effects on subtle organismic functions, such as would be expressed as alterations in mood, personality, general well-being, circadian rhythmicity (affecting sleep/wake patterns and their extensive biochemical substrates) may not lead to easily recognized pathological states, but may nonetheless be undesirable, negative health influences.

11. Illness, may occur after a latent period, making its cause more difficult to discern.

12. Illness may be limited to so few "susceptible" individuals that statistical detection of those individuals within a small exposed population is impossible.

13. The absence of an established "electric field syndrome" may indicate either the absence of any such health effects or the paucity of persons exposed under the requisite conditions of field strength, frequency and duration.

14. The mobile activity pattern of most people suggests that if there were restricted values of the field strength, frequency and duration parameters at which pathological changes occur, effects may be seen in controlled laboratory studies, but be entirely absent under realistic living conditions.

15. The possible accumulation of effects from repeated exposure is unknown.

16. The epidemiologic data which seem to show a weak relation between certain cancers and very weak magnetic and/or electric fields indicate a situation in which laboratory research would be exceedingly difficult in the absence of a dose response relation that extends over several orders of magnitude in field strength. It may be impossible to demonstrate a doubling in the incidence of a particular cancer with an ordinarily low rate of incidence if the experimenter cannot markedly increase the rate of incidence in the test laboratory animals by use of a large "dose". Because epidemiologic data can only indicate statistically suspicious occurrences but cannot show a cause and effect relation, such weak effects may remain unsubstantiated (or unrefuted) by good laboratory data for a long time.

17. It is certain that any electric field interaction would be characterized as a process of information transfer to the biological system rather than as one of energy transfer (as by heat or mol-

ecular excitation, etc.). With this in mind it is more reasonable to speculate that 60 Hz is a benign frequency than it is to speculate that the 60 Hz sinusoidal waveform would carry information coded to disrupt normal information processing at the cellular or organismal level. The spectrum of the transmission line electric fields (as for laboratory experimental fields) is quite pure, and essentially free of high order harmonics. Within the home or at work places where electricity is utilized by various electro-mechanical or electronic machines, the harmonic content is likely to be enhanced, perhaps with a greater likelihood for biological interaction due to the broader frequency spectrum. But it is unlikely that higher harmonics of 60 Hz would be biologically important, inasmuch as all evidence favors a preferential effect for the low frequencies typical of biological processes, e.g., the low frequencies which are dominant in brain waves.

2. Conclusions on Occurrence of Adverse Biological Effects

As a group, the foregoing factors lead to the conclusion that a strongly expressed biological effect in humans is not very likely, and to the further conclusion that a pathological effect is even less likely.

Adverse Effects in Humans are not Proven - The foregoing review of research in laboratory animals and the few studies of humans leads to the conclusion that pathophysiological effects in human beings exposed to 60 Hz electric fields at any field strength are unproven and speculative. Similarly, subtle effects on the nervous system that may alter mental state, disrupt normal body rhythmicity, alter libido, increase the frequency or severity of headaches, or lead to effects on digestion or other functions influenced by the central nervous system, are not demonstrated by the scientific research to date. The existing data do not permit the prediction that effects such as those just listed would occur as the result of chronic exposure to electric fields.

The field effects that have been demonstrated in several animal studies suggest it is reasonable to expect that humans exposed to appropriately scaled electric fields may show physiological or behavioral alterations related to those observed in animals. The pathological potential of the alterations cannot be foreseen.

Negative impacts on human health have not been established by the few studies of humans. These however are limited in scope and often methodologically flawed. They do not form the basis for a conclusion that chronic exposure to 60 Hz electric fields at arbitrary field strength is without effect for the general population.

3. Recommendations on the Electric Field at the Edge of the ROW

a) **It is recommended that the electric fields produced by the proposed BPA 500 kV transmission lines are sufficiently intense that regulations intended to limit chronic exposure are a prudent requirement.**

b) **It is recommended that the Colstrip Project 500 kV HVTL be constructed and operated so that the maximum electric field at the edge of the right of way (EoROW) does not exceed 1 kV/m.** This value is suggested on the basis of an analysis of the current scientific literature that concerns the biological effects of electric fields at 60 Hz and other low frequencies. The literature does not disclose specific hazards of chronic exposure, but there are sufficient well founded results to require reasonable precautions. These precautions aim to insure that HVTL electric fields do not occur at levels which might have an effect on the health of a person chronically influenced by exposure to the transmission line electric field.

c) **It is recommended that the maximum electric fields of the proposed line do not pose a health and safety hazard for acute effects so long as usual good engineering and construction practices are followed to limit currents induced on metallic structures near the line.** The maximum electric fields of the line pose their greatest practical hazard in the situation that a person receives a spark discharge of sufficient magnitude to produce a startle reaction which promotes an accident with a tool, machine or vehicle. This hazard is not sufficient to limit access to the right of way, although under some circumstances individuals such as farm machinery operators may require assistance in order to mitigate the occurrence of spark discharges when working beneath the line.

Adoption of the 1 kV/m EoROW standard and enforcement of customary sound engineering practices to limit voltages and currents induced on metallic structures near the line are prudent steps that, on the basis of current information, provide a wide margin of safety for both chronic and acute effects.

4. Conditions that Influence the Recommended Regulation of HVTL Electric Fields

It is not clear if the requirements for "chronic exposure" can be met under realistic living conditions, but regulation is recommended under the presumption that the transmission line electric fields present a chronic influence on persons regularly living or working near to the ROW.

There is considerable practical experience of public exposure to the weaker electric fields near lower voltage transmission or distribution lines and in the home or work place that has not yet elicited evidence of any adverse effects. The recommended criterion tethers the permissible range of electric field strengths to values for which there is the advantage of wide acceptance. Of course, commonly accepted practice may be erroneous, but a reexamination of common practices would involve nearly all aspects of a society that is replete with devices that use electricity. That examination is not required for the purpose of establishing safe practices with transmission lines.

In addition, ancillary issues provide practical limits on the levels at which an electric field standard can be established. Without regulation, the maxiumum ground level fields of a 500 kV circuit would just exceed the levels at which hair-related perception of the field (apparently the most sensitive form of human perception) occurs for most persons (7 kV/m), and the fields at the proposed EoROW would exceed the lower limits of perception found for sensitive subjects (1 to 2 kV/m). Similarly, ground level fields in excess of the median levels for annoyance (>20 kV/m) cannot occur with a 500 kV circuit, but fields in excess of the annoyance levels of some persons (5 kV/m) are possible. In practice, when the effects of spark discharges are included, the median values for perception range near 1.5 to 3 kV/m and those for annoyance range from 4 to 7 kV/m. (Q.v., Deno and Zaffanella, 1982 for the foregoing perception and annoyance criteria.)

5. The Conservative Nature of and Edge of the Right of Way Electric Field Criterion

The EoROW criterion is conservative because persons do not remain there for long periods. The electric field strength at the EoROW is greater than the space- and time-averaged electric field to which persons might be exposed under practical circumstances, and thus does not represent the electric field to which any persons would be chronically exposed.

Field variations produced by the sag of the line are significant only for points within the ROW. Near a tower, the electric field is reduced by the shielding effect of the tower. But at points far from the line (outside the ROW) the changes produced by variations in line height, or by the tower are of little importance.

Within, broad limits, a recreational facility off the ROW might constitute a situation for chronic exposure. This is perhaps a partial exception to the argument that chronic exposure to the EoROW field is very unlikely.

The exposure criterion recommended herein does not depend upon the aforementioned conditions that mitigate actual exposure and add to the margin of safety that is required to protect public health and safety.

6. Other Possible Electric Field Exposure Criteria

An edge of the ROW criterion is only one of several that might be considered. For example, were there sufficient evidence to indicate that acute exposure to strong electric fields posed a health hazard, it would be necessary to either limit access to the ROW or to impose a criterion for the maximum field strength anywhere on the ROW.

It may be considered reasonable only to regulate the electric field at inhabited sites, such as within homes or possibly at sites where people spend considerable time, such as recreational facilities or the backyards of homes. Under such a plan the location of houses, possible shield wires, and the effective shielding of the structures would be the focus of regulatory activity instead of the electric field at a particular distance from the line.

7. The Null Hypothesis Cannot Be Established with Certainty

No amount of data can prove the absence of a health risk because proof of the null hypothesis (that there are no harmful consequences of electric field exposure) can only be had by exhaustion of all conceivable tests. Since it is always possible to devise a new test, there can never be a complete proof of the absence of effects. Also, one can require unlimited degrees of statistical certainty for any negative finding, for example, up to such an absurd point as a requirememt that the rate of incidence is less than one case in 100 billion persons per 100 years. It is important to recognize that absolute safety is not obtainable, as shown by the logic of the foregoing. However absolute safety is not a requirement for social acceptance of the risk associated with technological devices or for individual acceptance of risk in general.

8. Basis for the Recommended Electric Field Criterion

The following factors have been taken into consideration in determination of a recommended electric field criterion for the EoROW.

1. Health and safety of humans exposed "chronically" in the course of work or residence adjacent to the ROW.

2. In a population there are persons with varying degrees of susceptibility to environmental agents. The most sensitive individuals may react to fields much weaker and presented for shorter periods of time, as compared to the average person.

3. The uncertain status of research into the biological effects of 60 Hz (or other extremely low frequency) electric and magnetic fields. The present research shows that biological interactions occur, but so far pathological effects resulting from exposure to electric fields have not been proven in laboratory animals. These results emphasize the need for caution, but the data do not permit extrapolation to say that human exposure to transmission line electric fields would result in diminished health. With respect to internal or external electric field strengths, some of the animal research is relevant to the issues of human exposure and provides a basis for judgment of the extent of possible health effects.

4. Animal research demonstrates perception of weak electric fields by an unknown mechanism which recent research suggests may not depend upon body hair.

5. The experience of workers in the electric utilities is that no effects on health were seen consistently in tests of a relatively few linemen or tests of larger numbers of switchyard workers. No self-reported or otherwise obvious effects of work in very strong electric field regions are reported. Anecdotal reports (Deno and Zaffanella, 1975, p. 264) indicate that workers exposed to the

influence of spark discharges suffer unpleasant changes in well-being. These reports are superficialy similar to the experience of workers in the USSR where spark discharges are cited as unfavorable working conditions. Preliminary evidence from switchyard workers in Sweden points to possible genetic effects for which there are no corrobative data from other studies. Laboratory research to support the chromosomal changes seen in white blood cells from these workers is entirely negative for evidence of genetic effects of HVTL 60 Hz fields, or in the case of a recent study using spark discharges (Hansson Mild et al., 1982) of uncertain applicability to human exposure conditions.

9. Preceding Electric Field Exposure "Standards" or Accepted Practices

- Faced with similar issues, but at a time when considerabley fewer laboratory data were available, the Public Service Commission of the State of New York permitted construction of a 765 kV (AC) transmission line with a right of way restriction that effectively limits the electric field at the EoROW to 1 to 2 kV/m.

- Under ordinary circumstances, the electric field at the EoROW of a 365 kV (AC) transmission line is 1 to 2 kV/m. There were 31,600 miles of HVTLs at this voltage in the United States in 1978, more than twice as many miles as for 500 kV (Kavet, 1981).

- The maximum ground level electric fields associated with transmission and distribution below 365 kV are generally below 1 to 2 kV/m.

- The electric field strengths within the home are generally below 100 V/m, and many persons voluntarily use electric blankets which subject them to much greater fields for several hours per day.

- Transmission line and substation workers are exposed to electric fields of more than 10 kV/m and the linemen are sometimes exposed to greater than 100 kV/m for periods of several hours per month. Average exposure of utility workers is low (e.g. < 1 or 2 $kV.m^{-1}$ h/day, Male, et al, 1982).

- In the USSR, electric field exposure to substation workers is unregulated below 5 kV/m, but limited to various exposure times for electric fields above 5 kV/m.
- In the USSR, electric field exposures of the general public are effectively limited to approximately 1 kV/m due to regulations prohibiting dwellings, recreational and work sites within 40 m of the outer (sic) conductor of 750 kV transmission lines (Lyskov, Emma and Stolyarov, 1975, pp. 12 - 13). However, the USSR has not yet approved a standard for the general population residing or working near transmission lines.

None of the above precedents for human exposure to chronic electric fields is based upon scientific demonstrations of harm produced by exposure to electric fields. The USSR work rules recognize the pathological nature of the joint effects of fields and spark discharges as concluded from studies of exposed workers, practical experience and laboratory research.

If electric fields strongly affected the health of persons exposed in any of the above existing situations, there would be significant anecdotal or medically supported evidence, apart from the experiences of USSR and Spanish switchyard workers. Precedent suggests, but does not prove, that none of the above situations involves a major health risk. It would be illogical to limit the electric field at the EoROW to a value lower than that tacitly accepted by persons using electricity in the home. For this reason, electric fields of 1 to 200 V/m may be considered in the range of "accepted practice", and until demonstrated otherwise, exposures in this range may be used to set a lower limit to the range of acceptable field strengths. On the basis of precedent, electric fields below about 100 V/m are accepted as "safe" by large numbers of people, while a small number of people engaged in transmission line work accept short-term exposures to fields in excess of 100 kV/m without indication of a health effect. The precedent of the USSR switchyard workers suggests that 5 kV/m is an upper bound for prolonged exposure to the joint influence of the field and associated spark discharges.

In summary, precedent suggests a restriction of electric field exposures to a value below about 10 kV/m, but not below about 100 V/m. That is, precedent suggests consideration over a range that varies by a factor of 100, bracketed by industrial experience at the upper end, and by consumer experience at the lower end.

It must be borne in mind that precedent is not a reliable indicator of safety, as it represents numerous psychologically determined tradeoffs that are defined on the basis of situation.

10. Risk-benefit Analysis

Risk benefit analyses are suggested as a means to quantify the costs incurred by the use of a technology and to make a tradeoff of the risk-associated costs against the benefits of the technology. Quantitive analysis of the risks of electric fields cannot be made on the basis of any existing data, although Rish and Morgan (1979) have tried to bracket the various costs in controlling exposure in an example applied to the health effects of transmission lines. The results of their analysis suggest that there is little cost in regulating the 500 kV line of their example to a 1 kV/m electric field at the EoROW, while the same standard requires added costs for shielding or for additional ROW, when applied to a 765 kV transmission line. Their analysis gives guidance to a choice on the desired strategy of controlling electric field strength at the EoROW depending upon population density, assumed health costs, and assumed threshold levels for the onset of a health impact due to chronic exposure to electric fields.

With regard to the benefits of electricity, few persons in our society would deny the overall value of reliable and affordable electric power, although there are many issues that arise concerning particular projects or the routes of particular transmission lines. These issues and the quantification of the industrial, personal and health benefits of electricity are outside the scope of this report.

In summary, risk-benefit analysis cannot at this time be used to guide the selection of an electric field criterion for human exposure.

11. Margin of Safety for Chronic Effects

Laboratory experiments suggestive of chronic effects of electric fields have generally involved continual exposure (20 to 24 hours per day). Under practical circumstances no person would be exposed to the HVTL field above 1 kV/m for a continual period. A person within a house located at the EoROW would be significantly shielded from the electric field, although data for various structures are not available at this time.

Most laboratory studies suggesting possible chronic effects involve (scaled) electric fields in excess of 1 kV/m, although (scaled) fields of the level already accepted in the environment (below 100 V/m) have been implicated in a few laboratory studies.

12. Margin of Safety for Acute Effects

There is no evidence for a health effect of short term exposure. On the basis of total body current, the maximum electric field produces too little current to be of concern as a shock hazard, with the possible exception of steady-state shock currents to children. Electric fields off the ROW could not result in currents hazardous to adults or children.

13. Flexibility and Uncertainty in the Recommended Electric Field Criterion

It is clear that the data do not define a single value that should be applied as an electric field criterion at the EoROW. The value selected appears to be a practical value, but it was arrived at without a conscious attempt to take into account the actual electric fields produced by a 500 kV transmission line, and thus without taking into account the costs that may be associated with enforcement of the recommended criterion.

If such costs are substantial, it would be important to know if an indistinguishable degree of safety could be achieved by adoption of a higher criterion, for example, 2 or 3 kV/m. In like manner, others might question if a greater degree of safety would follow from adoption of a lower criterion value, for example, 0.5 or 0.3 kV/m. The scientific evidence does not define the criterion value to within small factors such as two or three. However, a substantial elevation of the EoROW criterion to a level at which persons would directly perceive the field under practical circumstances, although far below the levels at which a person would be annoyed by the field, is not recommended.

On the other hand, substantial revision of the criterion to a much lower level appears unwarranted since the regime that begins at field strengths significantly below the suggested 1 kV/m criterion encompasses the range of electric fields found with older transmission and distribution technologies, and that found in the ordinary household environment. At the present time there is no need to consider regulation at these lower field strengths.

Because of the uncertainties that attend the selection of any one figure, and in light of possible extreme costs that would have to be borne by the public without a clear evidence of danger, the final decision on width of the ROW may require revisions based on considerations other than biological effects. Such revision may be the specification of a different field strength criterion or a criterion that is not applied to the EoROW, but still provides the same degree of protection from chronic exposure to fields above about 1 kV/m. For example, effective limitation of chronic field exposure can be achieved by alternatives such as a variable width for the right of way or by use of shielding.

GLOSSARY

alternating current - an electric current which changes in polarity periodically.

alternating electric field - the electric field produced by an alternating voltage.

alternating voltage - a voltage which changes in polarity periodically.

axial current, axial current density - the portion of the total current or current density that flows along a particular direction (the "axis"); e.g., in a laboratory animal the portion of current that flows along an axis parallel to the spine.

biophysical - relating to the physical properties of biological organisms, tissues, cells, etc. E.g., the conductivity of tissue or the internal electric field strength are biophysical quantities.

circadian rhythm - daily cycle of certain physiological processes such as activity, temperature and as indicated by the levels of electrolytes, hormones, neuromodulators, etc. in body fluids or tissues.

controls - animals not subjected to the field or other experimental treatment; see also sham exposed.

current density - the flow of electric current across a unit area, a measure of the concentration of current within the object or body tissues; measured in amperes per square meter (A/m^2), or often microamperes per square centimeter (uA/cm^2), etc.

effective field - the time-averaged electric field to which a laboratory animal is exposed; this field is less than the unperturbed field because of mutual shielding by animals housed as a group.

electric field - concept used to represent the energy due to the location of electric charges at various sites in a region; the HVTL electric field is an alternating (60 Hz) field due to the charges of alternating polarity that are located on the conducting wires of the transmission line. Electric fields are capable of performing work on other electric charges.

electric field strength - magnitude of the electric field, measured in volts per meter, volts per centimeter; see volt per meter. The electric field strength beneath a HVTL is generally measured at a fixed height above ground (usually 1 meter).

ELF - abbr. for extremely low frequency

EoROW - edge of right of way; the margins of the transmission line ROW.

extremely low frequency - a frequency between 3 and 300 Hz; loosely, any frequency below about 100 Hz.

Faraday screen - see Faraday shield

Faraday shield - a conducting material used to enclose an object in an electric field; the electric field is conducted by the material (usu. copper wire) thereby reducing to nearly zero the electric field at the enclosed object.

G - abbr. for gauss

gauss - unit of magnetic field induction (B-field); numerically equal to the oersted, the unit of magnetic field intensity for non-magnetic objects (such as air, biological bodies); equal to 10^{-4} Tesla, the preferred (MKS) unit of magnetic field induction.

Hertz - the unit of time variation for an alternating current or field. Syn. (obs.): cycle per second (cps).

horizontal electric field - an electric field directed parallel to the earth's surface; in the laboratory such fields are created by vertical plates.

HVTL - high voltage transmission line; typically one operating at or above 345 kV.

Hz - abbr. for Hertz

impedance - the physical property of materials that determines the relation between current flow and potential difference in the material; for direct currents, impedance is identical to resistance; for alternating currents impedance includes the properties of resistance, capacitance and inductance.

impedance to ground - an impedance measured between an object and earth ground; in caged laboratory animals this property depends upon the caging materials, construction and electrical design, and the biophysical properties of the animal's footpad; for humans, skin, clothing or shoe properties are significant.

incident electric field - analagous to the incoming field in optics; see "unperturbed electric field".

internal electric field - electric field strength measured, or calculated for points within the body of an animal or human exposed to an electric field.

kilovolt per meter - 1000 volts per meter; see volt per meter.

kV/m - abbr. for kilovolt per meter.

m - abbr. for milli, the prefix for 1/1000 -th, e.g., mV, for millivolt.

m - abbr. for meter.

mA/cm^2 - abbr. for milliampere per square centimeter; a unit of current density.

magnetic field - a concept to describe the energy produced by moving electrical charges such as those in an electrical current; the transmission line magnetic field is due to the flow of current in the wires. A magnetic field can perform work on moving electric charges, such as those in another wire carrying current or in a moving wire (dynamo principle).

micro - prefix for one-millionth; e.g., microvolt, microampere, micrometer; abbr. as u [Greek letter mu].

microtesla - one millionth of a Tesla.

milli - prefix for 1/1000 -th; e.g., millivolt, milliampere.

mV - millivolt; 1/1000 -th of a volt.

mV/cm - millivolt per centimeter; unit of electric field strength suitable to some fields produced in body tissues by strong external electric fields.

neurophysiologic - relating to the function of the nervous system or its components such as the brain, spinal cord, the sub-divisions of those organs and their cellular components, including the nerve fibers.

right of way - strip of land on which a transmission line is sited.

ROW - abbr. for right of way

scaling - relating an exposure of one animal species to another so that one can interpret the effect of the electric field on an equal basis; because of shape and orientation dependence for both internal and external fields, humans and animals exposed to the same unperturbed field have very different fields acting on the body; in general humans experience greater surface fields and much greater internal fields than do quadruped animals in the same unperturbed field.

sham exposed - a control experimental condition in which the animals, tissues, etc. are treated identically to the exposed objects, except that the field or other treatment is not present; distinguished from "controls" by the use of apparatus that is in all ways identical to the exposure apparatus and which in other trials is used for actual exposures. Used where it is necessary to assure that some aspect of the exposure apparatus apart from the field could not influence results. Regarded as a superior form of control technique, and may be used in conjunction with separately caged controls ("cage controls").

surface electric field - the electric field at the outer margin of the object or body; this field is influenced by the shape of a conducting body and depending upon the degree of curvature is greater than the unperturbed electric field.

teratologic - relating to abnormal anatomy, resulting in deformities, fetal death, still birth etc., especially in a developing or newborn organism.

Tesla - unit for magnetic field induction (B-field), equal to 10^4 gauss, and equivalent to 10^4 oersted for non-magnetic media.

Unperturbed electric field - the field that that would exist at the body's location if there were no body located in the electric field. In the case of a uniform field, the field that exists far from the location of a conducting object (such as the human or animal body).

uA/cm^2 - abbr. for microampere per square centimeter, a unit of current density.

uT - abbr. for microtesla.

vertical electric field - an electric field directed perpendicular to the earth's surface; in the laboratory such fields are created by horizontal plates.

volt per meter - unit of electric field strength; a field of one volt per meter is created by two flat plates separated by 1 meter and having a potential difference of 1 volt.

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